

BUILDING RESILIENCE TO CLIMATE CHANGE: IMPACT OF MULCHING ON THE SOIL WATER BALANCE AND POTATO GROWTH

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ABSTRACT

Climate change has a significant impact on agricultural production because of its reliance on environmental factors. Like in most parts of the world, the climate in Belgium is changing with projections of increase in winter precipitation and decrease in summer precipitation. With accompanying higher temperatures, evaporation will increase, and water availability will decrease, especially in summer. It then becomes necessary to efficiently manage soil water for sustainable crop production. While conservation agriculture is a promising climate smart agricultural technology, it is often considered with less focus on mulching, one of the pillars of CA. In cases where mulching has been studied, it was mostly under conventional tillage system, and about yield and greenhouse gases emission. Since there is no one-size-fits all on soil water management. It is imperative to conduct strategies suitable to local conditions. Potato is a staple crop in Belgium, and it is drought sensitive. This makes it susceptible to effects of climate change. Therefore, this research studied the impacts of mulching, under reduced tillage, on soil water balance and potato growth as an adaptation strategy to climate change in the Flemish agricultural context.

A field experiment was conducted on a bio-parcel of the Flanders research institute for agriculture, fisheries and food in Melle, East Flanders, Belgium. This study evaluated the effects of two different mulch thickness (6 cm and 12 cm) against bare soil (no mulch) on evapotranspiration (ET), potato growth, yield and water use efficiency (WUE). An adapted soil water balance equation was used to determine ET; plant height and leaf area index (LAI) were used as parameter of crop growth; and WUE was determined as a quotient of yield and ET. Data collected were subjected to analysis of variance and significantly different means were separated using Tukey's Honestly Significant Difference (HSD) at 5% level of significance.

This study revealed that soil structural quality and soil water content improved under mulch; 12 cm mulch performed best in preventing drought stress during low rainfall; ET increased with increasing mulch thickness though not significantly; 12 cm mulch significantly increased LAI compared to other treatments; and yield and WUE were not significantly different among the treatments though 6 cm and 12 cm mulch increased yield by 7.4% and 10.9% respectively.

Keywords: climate change, conservation agriculture, soil water management, mulching, water use efficiency.

1.0 INTRODUCTION

1.1 Background to the Study

There is a complex set of interactions among the atmosphere, hydrosphere, lithosphere, and biosphere that controls the earth's climate system. In its Article 1, the United Nations Framework Convention on Climate Change defines climate change as “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods” (Sivakumar, 2021). Over the past few decades, climate change has become one of the critical global issues, which has serious implications for sustainable development generally (Sivakumar, 2021).

According to the sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), human activities have led to global surface temperature reaching 1.1 °C above 1850 - 1900 in 2011 - 2020, and new estimations reveal that the globe is close to exceeding the 1.5 °C limit (IPCC, 2023). The World Meteorological Organization, WMO, confirmed 2023 as the warmest year as global surface temperature was 1.45 ± 0.12 °C above pre-industrial levels (WMO, 2024). Also, there have been more frequent and intense extreme weather events, and uncertainty in rainfall patterns which all have significant impacts on food production and food distribution (Sivakumar, 2021; IPCC, 2023).

Climate change has a significant impact on agricultural production because it is reliant on environmental factors (Arora, 2019). The cultivation of soil and management of crops require proper weather and climatic conditions. For instance, the application of agro-chemicals or tillage of soil would be determined by weather conditions. More so, the distribution of crops in different geographical regions, cropping patterns, management inputs, and crop growth and phenology are all influenced by climatic factors such as temperature, precipitation, and photoperiod. For instance, droughts, flash floods, untimely rains, frosts, hail, and storms cause a decline in agricultural production (Hay, 2007; Ray *et al.*, 2019; Schmitt *et al.*, 2022).

Because of intensive farming using conventional tillage practices, food production has shown significant growth in developing countries, especially China, under the Green Revolution technologies from 1960 to 2010 (Shen *et al.*, 2013). This has decreased the proportion of humans

suffering from hunger (Shen *et al.*, 2013). To this day, ploughing and rotary tillage for land preparation are still commonly practiced by farmers. However, such conventional tillage exacerbates soil disturbance and harms soil health, making it an ineffective means of enhancing agricultural resilience to climate change (Deng *et al.*, 2022).

With climate change comes an increase in temperature and erratic rainfall pattern (Tun Oo *et al.*, 2023). These interfere with soil water balance and crop growth as there is increase in soil water loss through evaporation (Bai *et al.*, 2012) and decline in soil organic matter resulting from faster rate of decomposition (Bindi & Olesen, 2011). These effects are further exacerbated by management practices, especially conventional tillage, and land use change (Jin *et al.*, 2017). To address these challenges of soil degradation and food insecurity, conservation agriculture seems promising. Conservation agriculture involves three principles of minimum soil disturbance (by reduced or no tillage), permanent soil cover (by mulch, cover crop, or residue retention), and crop diversification (Hobbs *et al.*, 2008; Pittelkow *et al.*, 2015). In fact, it has been identified as a method to increase agriculture's resilience to climate change (Michler *et al.*, 2019).

Agriculture is one of the most sensitive sectors in response to climate change, as crop production is highly dependent on environmental factors. It is the foundation of human survival which has a significant influence on food security, industrial development, and social stability, and has received extensive attention due to its significant status. In response to the impact of climate change on agriculture, the concept of "climate resilience" has been introduced to help improve agriculture's ability to cope with climate change (Deng *et al.*, 2022).

In the light of climate change, the IPCC defined resilience as the "ability of a system and its component parts to anticipate, absorb, accommodate, or recover from the effects of a hazardous event in a timely and efficient manner" (Field, 2012). In an agricultural context, El Chami *et al.* (2020) advocate that resilience refers to the capacity of agricultural systems to respond to social, economic, and environmental changes via structural reorganization, to offset the impacts of future changes, and to engage in new opportunities, to ensure the continuity of agrosystems. Focusing on climate challenges faced by agriculture, Deng *et al.* (2022) argued that "climate resilience" refers to the ability to maintain agriculture's core functions, including food security, soil and water conservation, and economic growth, while mitigating the impacts of climate change.

One way to build the resilience of agriculture to climate change is the practice of soil-water conservation techniques to make water sufficiently available to crops at different phenological stages, thereby maximizing the crop potentials in terms of growth, development, yield, and water productivity (Agus *et al.*, 2015, Chouhan *et al.*, 2023).

1.2 Justification of the Study

The impacts of climate change on agriculture are observed on global, regional, and local scales (IPCC, 2001). Like in most parts of the world, the climate in Belgium is changing. The mean annual temperature increased by 2°C and mean winter precipitation increased by 15% between 1833 and 2009 (Brouyaux *et al.*, 2009). Further, projections have estimated that by 2100, winter precipitation will increase by 3 – 50% while summer precipitation will decrease up to 50% (Ntegeka & Willems, 2008). Moreover, evaporation will increase with higher temperatures (Boukhris *et al.*, 2008) and the water availability will decrease, especially in summer (Manabe *et al.*, 2004).

Some of the secondary effects of climate change include drought and flooding (Dupont & Van Eetvelde, 2013), and one of the possible adaptation responses is change in soil and water management (Tubiello & Rosenzweig, 2008) from conventional to conservative practices that align with conservation agriculture. Conservation agriculture (CA) is being adopted in different parts of the world at different rates, and Europe still lags in this regard due to various reasons highlighted by Kertesz & Madarasz (2014). In fact, Europe is regarded as a developing continent in terms of CA adoption. Though several studies have investigated the agroecological and economic impacts of CA, the focus has been on conservation tillage with other pillars of CA less considered. Interestingly, the focus has been on how reduced or zero tillage impact crop yield or mitigates greenhouse gases emission whereas other pillars of CA such as mulching have not been well studied or adopted (Basch *et al.*, 2015; Ghaley *et al.*, 2018; Gonzalez-Sanchez *et al.*, 2022). Hence, there is a need to optimize the practice of CA in Europe and embrace other potential benefits it has beyond crop yield. Despite positive outcome of Belgium's first experience with CA, it is one of the two countries with the least area under CA (about 270 ha) as at 2018/2019 (Gonzalez-Sanchez *et al.*, 2022). Moreso in Belgium, mulching is not a common practice for soil water conservation and crop growth though some studies have considered how plastic mulching modifies the population of pathogens and saprophytic fungi in the soil (Welvaert & Poppe, 1986).

Several studies have majorly considered the influence of mulching, as a conservation practice in conventional agriculture, on soil properties and crop growth. It is found to improve soil porosity, available water capacity, and infiltration but reduce soil evaporation and runoff (Blanchy *et al.*, 2023). While these studies have been considered in different locations, there is no “one-size-fits-all” solution (Heitman *et al.*, 2023). Therefore, it becomes imperative to study how mulching under reduced tillage system can impact soil water, in the face of potential drought attributable to climate change, in Belgium. Further, how does this soil management practice impact crop growth especially potato, an important food crop in Belgium which is drought sensitive.

1.3 Aim and Objectives

This study, therefore, aims to evaluate the influence of mulching on soil water balance and potato growth in the Flemish agricultural context.

Specific objectives of this study are to:

- Evaluate the effect of mulching on evapotranspiration, particularly soil evaporation.
- Evaluate the effect of mulching on potato growth and yield.
- Evaluate the effect of mulching on water use efficiency (WUE).

1.4 Research Question

This study intends to answer the question: “How does mulching under reduced tillage influence soil evaporation, and subsequently influence available water for plant growth, as an adaptation mechanism against extreme weather conditions, in the Flemish agricultural context?”

1.5 Research Hypotheses

The research hypotheses for this study are as follows:

- 1 Mulching reduces soil evaporation as compared to control.
- 2 Mulching increases water availability for plant uptake in the process of transpiration.
- 3 Mulching enhances crop growth and yield.

2.0 LITERATURE REVIEW

2.1 Climate Resilience

Bieling *et al.* (2011) described resilience as the ability of a system to deal with disturbances or change without altering its essential characteristics. This involves anticipating, absorbing, accommodating, or recovering timely and efficiently from such disturbances. While disturbance or change (especially climate change) may be inevitable, a system may be able to better cope or deal with it if relevant measures are put in place. Agricultural systems, sometimes referred to as “agrosystems” (El Chami *et al.*, 2020) are largely susceptible to the impact of climate change, and to help improve their ability to cope with climate change, the concept of “climate resilience” has been introduced (Deng *et al.*, 2022)

Agriculture’s resilience to climate change is the capacity of agricultural systems to compensate the impacts of likely social, economic, and environmental changes, and ensure its continuity of agrosystems by engaging new opportunities (El Chami *et al.*, 2020). Focusing on the link between agriculture and the environment, climate resilience is described as agriculture’s ability to maintain its fundamental functions of food security, soil and water conservation, and economic growth in the face of climate change (Deng *et al.*, 2022). For efficient food production, sufficient soil water must be available for plant uptake. This is dependent on the balance between water gain and water loss in the soil, a concept known as soil water balance.

2.2 The Concept of Soil Water Balance

The soil water balance can be described as the amount of water stored in the soil resulting from the difference between the water flux in and out of the soil over a given soil thickness, usually between the soil surface and maximum root depth, over a period. This amount of water stored is sometimes referred to as soil water storage (Smika & Unger 1986; Unger, 1986; Zhang *et al.*, 2011; Elsheikh, 2015). Water flows into the soil from natural and artificial sources, that is, precipitation, irrigation, and capillary rise from the groundwater table, while water leaves the soil through drainage of water out of the root zone by gravity, runoff of water that does not infiltrate, evaporation of water from the soil surface, and water absorbed by plant roots for transpiration (Ritchie, 1998).

The water balance of a soil profile over a given period can be defined as (Cornelis *et al.*, 2002):

$$\Delta S = P + I - ET - R - D + L_i - L_o \quad (1)$$

where ΔS is the change in soil water storage, P is the precipitation, I is the applied irrigation water, ET is the evapotranspiration (or evaporation in case of a bare soil), R is the surface runoff, D is the drainage (if positive) or capillary rise (if negative), and L_i and L_o are lateral inflow and outflow, respectively. All components are expressed in units of length. Drainage of water out of the rootzone is often referred to as deep percolation.

These components referred to as budgetary considerations influence the water economy in the root zone of a soil profile (Ritchie, 1998). This water economy is a critical determinant of plant biophysical activity. Moreover, model simulations provide tools to gain insights into these different water balance components (Zhang *et al.*, 2007).

2.3 Components of the Soil Water Balance

2.3.1 Precipitation and Irrigation

Precipitation is the primary source of water input into the soil. It includes rain, snow, sleet, and hail, that the soil receives from the atmosphere over a period. Irrigation becomes an alternative or an addition when the amount of rainfall is too low to cater for the water demand of a crop for a growing season, but it incurs additional production costs. Though studies (Galle *et al.*, 2001) have considered runoff from upslope as part of the water input, this is usually negligible when the field is considered almost flat, has a low slope, or if there is a barrier preventing runoff across fields in a landscape.

While other components of the soil water balance are usually calculated or simulated, precipitation, commonly as rainfall, is usually directly measured (Pirastru and Niedda, 2013). This is mostly done using a rain gauge, such as a graduated cylinder or a tipping bucket rain gauge (Cornelis *et al.*, 2002; Jin *et al.*, 2007).

The variability in rainfall frequency and intensity plays a crucial role in soil moisture dynamics, and for effective soil water management, it is important to maximize the amount of rain infiltrating the soil. But if the rainfall intensity exceeds the infiltration rate, some of the rain is lost as runoff. Another factor that hinders the infiltration of the total rain into the soil is interception by crop canopy and/or soil cover (Alliaume *et al.*, 2017).

2.3.2 Evaporation and Transpiration

Evaporation is the loss of water from the soil surface, while transpiration is the loss of water from plant leaves through their stomata. While evaporation is considered unproductive loss of water, transpiration is. This is because the latter facilitates the process through which plants manufacture their own food and grow. These two processes are sometimes considered together as evapotranspiration, which is the sum of the water lost from both the soil and plant surfaces. This is because both processes account for water leaving the land surface to the atmosphere and often occur simultaneously (Monteith, 1973; Allen *et al.*, 1998).

The process of evaporation is facilitated by the evaporativity of the atmosphere and the evaporability of the (soil) surface (Hillel, 2003). These involve conditions such as a continual supply of heat, a vapour pressure gradient and a continual supply of water from the surface. According to Asmamaw (2017), high temperatures could facilitate soil evaporation reaching 30 – 50% of the total rainfall leaving only 10 – 30 % for crop transpiration.

The concept of evapotranspiration can be considered in different forms, including reference or potential evapotranspiration (ET_0) and actual or crop evapotranspiration (ET_a or ET_c) (Stanhill, 2019).

The Food and Agriculture Organization of the United Nations (FAO) defines the reference evapotranspiration as the amount of water lost to the atmosphere from a surface of hypothetical grass with assumed height of 0.12 m, albedo of 0.23 and surface resistance of 70 s m^{-1} when water is not limiting (Allen *et al.*, 1998). For its determination, the FAO-56 application of the Penman-Monteith equation (Allen *et al.*, 1998) is widely used and considered as standard (Walter *et al.*, 2000):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad (2)$$

where ET_0 = reference evapotranspiration (mm day^{-1}), R_n = net radiation at the crop surface ($\text{MJ m}^{-2} \text{ day}^{-1}$), G = soil heat flux density ($\text{MJ m}^{-2} \text{ day}^{-1}$), T = mean daily air temperature at 2 m height ($^{\circ}\text{C}$), u_2 = wind speed at 2 m height (m s^{-1}), e_s = saturation vapour pressure (kPa), e_a = actual vapour pressure (kPa), $e_s - e_a$ = saturation vapour pressure deficit (kPa), Δ = slope of vapour pressure curve ($\text{kPa } ^{\circ}\text{C}^{-1}$), γ = psychrometric constant ($\text{kPa } ^{\circ}\text{C}^{-1}$).

Crop evapotranspiration (ET_c) is the evapotranspiration from crops grown on large fields with optimum soil water conditions, without disease and well-fertilized under a given climatic condition. It can be estimated as the product of ET_0 and a crop coefficient (K_c) (Allen *et al.*, 1998).

$$ET_c = K_c ET_0 \quad (3)$$

In soil water studies, crop evapotranspiration can be estimated from the general soil water balance equation when the other components are known. These components include precipitation, irrigation, runoff, drainage, capillary rise and change in soil water storage (Stephenson *et al.*, 2021):

$$ET_c = P - R - D - \Delta S \quad (4)$$

When studying soil water partitioning, especially as influenced by management practices, it becomes necessary to determine evaporation as a proportion of evapotranspiration. Soil evaporation can be measured using microlysimeters. This is done by keeping the soil in the microlysimeters similar to the surrounding plot and regularly weighing it to determine the amount of water lost through evaporation (Chen *et al.*, 2007). Another means of distinguishing soil evaporation from crop transpiration is the use of models such as Crop-Syst, SOILWAT2, and AquaCrop (Stöckle *et al.*, 2003; Paredes *et al.*, 2015; Chen *et al.*, 2023). Each of these approaches has its limitations. For instance, microlysimeter evaporation would likely be higher than the soil evaporation since the latter is affected by root water uptake. Also, model simulations can over- or under-estimate any of the parameters but can be improved upon. A study by Paredes *et al.* (2015) showed that AquaCrop tends to underestimate soil evaporation and pointed out the need to revise the estimation procedure. Regardless, any of these approaches can provide valuable insight into evapotranspiration partitioning when used with caution.

2.3.3 Drainage

Drainage is the discharge of water below a given depth as facilitated by gravity (Cornelis *et al.*, 2004). Although it may recharge groundwater, it is seen as an unproductive loss of water. It can be measured on the field using a lysimeter or drain gauge (Meissner *et al.*, 2020), but its installation can be laborious, time-consuming and is relatively expensive (Ben-Gal & Shani, 2002; Duncan *et al.*, 2016).

Another way to estimate drainage in soil water studies is by using the Darcy-Buckingham equation for steady state flow. It requires the assessment of the hydraulic conductivity curve which is then combined with tensiometer readings of soil water potential (Stephenson *et al.*, 2021). The drainage component reads then as (Jin *et al.*, 2007):

$$D = q\Delta t = -K(\bar{\theta}) \frac{d\bar{H}}{dz} \Delta t \quad (5)$$

where $K(\theta)$ is the hydraulic conductivity [$L T^{-1}$] corresponding to the volumetric water content of the soil θ , dH/dz is the hydraulic-head gradient, q is the soil water flux [$L^3 T^{-1}$], and the overbars denote time-averaged values.

The depth at which drainage is determined may vary based on the conditions of any study (Chen *et al.*, 2007; Jin *et al.*, 2007) as related to the groundwater level and root zone of the crop being considered. It usually represents the water flow at the maximum rooting depth (Cornelis *et al.*, 2004).

Drainage can also be determined using the plane-of-zero-flux method (Maesschalck *et al.*, 1985). This is a transitional plane in a soil profile above which there is an upward flux of water and below which there is a downward flux of water. Brutsaert (2014) defines it as the lower boundary of the capillary rise layer, below which water infiltrates downward by combined driving effects of the pressure gradient and gravity. When present in a profile, the water flux can be determined without needing the Buckingham-Darcy equation (Maesschalck *et al.*, 1985). Using this method, drainage is determined as the difference in soil-water storage between this plane and a given depth below for instances where rooting depth does not exceed it (Jin *et al.*, 2007). Its presence is determined from the hydraulic head profiles measured by tensiometers (Jin *et al.*, 2007). A limitation to this method is that the plane of zero flux may exist for short periods only under certain weather conditions. Hence, Buckingham-Darcy's equation is recommended for calculating soil water fluxes (Maesschalck *et al.*, 1985).

2.3.4 Runoff

Runoff is the portion of water supplied to soil surface which is neither absorbed by soil nor retained on its surface but runs downslope (Hillel, 2003). It is an unproductive loss of water. Runoff occurs when the rainfall rate exceeds the infiltration rate or when soil is saturated. It is driven by the land slope and is affected by soil properties such as texture, porosity, and aggregate stability. Another

factor is the antecedent soil moisture which may decrease infiltration capacity thereby increasing surface runoff (Asmamaw *et al.*, 2012). Also, increasing the roughness at the soil surface may slow down runoff water, giving the latter more time to infiltrate.

Intensive rainfall causes a high proportion of runoff that may facilitate soil erosion (Asmamaw, 2014). Runoff contributes to both water and soil loss, and adoption of conservation structures has been found to lower it (Gebreegziabher *et al.*, 2009; Oicha *et al.*, 2010). It has been a limiting factor to crop yield even when rainfall is sufficient (Temesgen *et al.*, 2009; Asmamaw *et al.*, 2012). While excessive soil manipulation leads to accelerated runoff due to deterioration of soil structure (Temesgen *et al.*, 2008), conservation tillage has been found to reduce runoff because it significantly increases soil water infiltration (Asmamaw, 2017).

Runoff can be monitored, on the field, with automatic discharge gauges (Cornelis *et al.*, 2004) or by using a flume with automatic discharges and a collector drum at the downslope bottom of a plot (Jin *et al.*, 2007). There have been several models developed that allow to simulate soil surface runoff such as ParFlow (Kollet and Maxwell, 2006), HydroGeoSphere (Brunner and Simmons, 2012) and surface water flow models on HYDRUS (Liang *et al.*, 2017). For a more comprehensive simulation of surface runoff that incorporates subsurface hydraulic connectivity when surface runoff occurs in multiple depressions, Wang *et al.* (2020) developed a physical-based surface runoff model based on the Saint-Venant equation and implemented it in 2DSOIL. After evaluation and application, the model proved reliable in simulating surface water movement over a variety of soil surfaces (Wang *et al.*, 2020).

However, many studies neglected surface runoff in their soil water balance evaluation because it was not observed due to high infiltration (Chen *et al.*, 2007) or because of low precipitation and flat topography (Biswas *et al.*, 2022; Zhang *et al.*, 2016).

2.3.5 Change in Soil Water Storage

Soil water storage can be considered over an entire profile (Zhang *et al.*, 2011) as a sum of the soil water stored at different depths or within a soil layer. This is typically assessed by measuring the water content at the start and at the end of a period which could be a developmental period, an entire growing period, a season, or a year. The difference in the soil water content over the period gives the change in soil water storage (Chen *et al.*, 2007; Jin *et al.*, 2007; Zhang *et al.*, 2011, Biswas *et al.*, 2022).

Measurement of soil-water content can be done with different direct or indirect methods. The direct method includes the determination of the gravimetric water content after soil sampling and multiplying it with the bulk density of the soil to get its volumetric water content. While this method can give an accurate measurement, it is difficult to use to determine the soil moisture content in a time series and can be destructive, laborious and time-consuming (Bittelli, 2011; Zhang *et al.*, 2020). This has necessitated using various indirect methods (soil moisture sensing) which not only measure but also monitor soil water content as they provide repeated moisture readings over time (binti Abdullah *et al.*, 2015). Some of them are further discussed.

The neutron gauge is regarded as the most accurate (Evet *et al.*, 2002) but it is expensive and difficult to use due to safety regulations (Huang *et al.*, 2004). Further studies have evaluated several sensors that could be better alternatives (Huang *et al.*, 2004, binti Abdullah *et al.*, 2015, Jia *et al.*, 2021). Among many options, soil moisture sensors based on electromagnetic (EM) techniques are most advantageous as they are accurate, can be applied in most soil types and plant growth substrates, show minimal soil disturbance and do not use ionizing radiation (Vaz *et al.*, 2013; Jia *et al.*, 2021). Regardless of the advantages of soil moisture sensors, they are usually calibrated using the gravimetric technique (Hrisko, 2020). EM sensors based on time domain reflectometry (TDR), or frequency domain (FD) are widely used to estimate the volumetric water content. These sensors, especially TDR, coupled with progress in waveform interpretation in field soils have made accurate measurements of field soil water contents at high temporal resolution attainable, but can be expensive and complicated (Schwartz *et al.*, 2008; Surya *et al.*, 2020). On the other hand, capacitance sensors are cost-effective, highly economical, and have been frequently used to monitor soil water content too, though soil specific calibration has been recommended for more accuracy (Kanso *et al.*, 2020). Such sensors use the dielectric contrast between soil and water to estimate soil water content from the amount of charge stored by soil under an applied electrical potential. And change in capacitance of the porous medium (soil) is an indication of change in its water content (Hrisko, 2020). Though Evett & Steiner (1995) reported poor precision of capacitance probes and Evett *et al.* (2002) reported erratic values from them, Yoder *et al.* (1998) reported that capacitance sensors were among the best performing in their study.

2.4 Effects of mulching on soil water balance, crop yield and water use efficiency

Mulching is a well-known and recommended practice to conserve soil and water (Becher, 2005). Kasirajan and Ngouajio (2012) defined mulch as a coating material spread over the soil surface. It can be organic when derived from plant and animal materials such as straw, wood chips, wood shavings, saw dust, paper, peanut hulls, grass clipping, dry leaves, compost, and animal manures; or inorganic when it is gravel, pebbles, crushed stones or plastic derived from polyvinyl chloride or polyethylene films (Bhardwaj 2013; Patil Shirish *et al.*, 2013; Wang *et al.*, 2021; Coelho *et al.*, 2022). Erenstein (2003) identified mulching as one of the promising technologies that is an integral component of conservation agriculture and is increasingly seen in the light of integrated soil management. It is defined as a technology whereby at least 30% of the soil surface is covered by organic material.

Mulching can therefore be defined as the protective covering of the soil surface around the plants with living or non-living material to make favourable conditions for plant growth and efficient crop production (Chakraborty *et al.*, 2008; Kader *et al.*, 2017). It has the potential to conserve soil moisture, improve soil ecology, minimize soil erosion, stabilize and enhance crop yield, and provide various environmental services (Erenstein, 2003; Kaur & Bons, 2017). This is because it is located at the soil-atmosphere interface and acts both as soil protector and soil amendment (Erenstein, 2003). Many factors contribute to the effects of mulching. They include type of mulch material, mulch thickness, mode of application, time of application, climatic conditions, and management practices under which it is employed (Kader *et al.*, 2017; El-Beltagi *et al.*, 2022; Souza *et al.*, 2022).

As promising as mulching is in conserving soil water and improving crop yield, factors such as availability, costs and application are important for farmers' consideration. This often requires finding the optimum rate of application without an excessive cost for farmers (Jordan *et al.*, 2010). Further, Mulumba and Lal (2008) emphasized the need for optimum application rate for improving soil available water content and soil physical quality for site-specific soils and environmental conditions.

2.4.1 Effects of mulching on soil water balance

Generally, mulching, in different environments, is found to reduce evaporation and runoff, increase infiltration and improve soil water available to plants at the root zone (Kader *et al.*, 2017; Ranaivoson *et al.*, 2017; Xiong *et al.*, 2018). On a well-drained loamy soil of the north China plain, Chen *et al.* (2007) found that 3 ton/ha and 6 ton/ha of straw mulch reduced soil evaporation by 16-25% and 37-53%, respectively. For chili pepper production on a silty loam in Bangladesh, Ashrafuzzaman *et al.* (2011) found plastic mulch, applied flatly, to increase soil moisture at 0 – 10 cm depth at 90 days after transplanting. 19.2 - 21.1% soil moisture was recorded using plastic mulch of different colours (transparent, blue, and black) while 14.6% soil moisture was recorded on the bare soil. McMillen (2013) reported that flat mulching with wheat straw, grass clipping and plant debris of 5 – 10 cm increased soil moisture by 10% in loamy sand compared to bare soil in California. In terms of runoff, Montenegro *et al.* (2013) found the flat application of rice straw mulch at 2 ton/ha and 4 ton/ha to reduce runoff by 21% and 51% respectively on a sandy loam obtained from Portugal. In a three-year field experiment in the Loess Plateau of China, Zhang *et al.* (2016) showed, by using a model calibrated on soil-water content data, that soil evaporation was reduced from 60-81% of precipitation to 46-72% of precipitation and that the change in soil water storage increased from 19-40% of precipitation to 28-52% of precipitation as an effect of mulching compared to conventional field management. Under the production of irrigated winter cabbage on a clay loam in a humid tropic of West Bangal, India, Biswas *et al.* (2022) found that 3 cm thick straw mulch significantly increased soil water storage by 25% compared to no mulch. A study by Chakraborty *et al.* (2008) reported a significant increase in soil moisture by applying mulch on a sandy loam in a semi-arid environment under wheat production. The study included five treatments - limited irrigation with no mulch, transparent polyethylene, black polyethylene, risk husk; and adequate irrigation with no mulch as control. Considering soil moisture at different depths and at different growth times, risk husk seemed to be the best in conserving soil moisture in both surface and subsurface layers from sowing to harvest, closely followed by transparent polyethylene.

Both plastic mulch and organic mulch significantly enhance soil water conservation. Though they both reduce evaporation, plastic mulch is more effective but with a drawback that it limits infiltration of rain into the soil. This makes it more suited for colder and drier regions than warmer and wetter regions. On the other hand, organic mulch increases soil surface roughness, reducing

runoff and increasing infiltration (Kasirajan & Ngouajio, 2012; Yu *et al.*, 2018). With the fact that organic mulches are more environmentally friendly and have additional benefit of improving soil nutrients, more studies are focusing on their impact on agriculture while preserving the environment (Bhardwaj, 2013; Patil Shirish *et al.*, 2013).

Some studies highlighted the positive impacts of mulching while others found neutral or negative impacts of it. Its positive impacts on soil water balance were observed in different production areas including arid or semi-arid, mediterranean, and humid subtropics environments (Deng *et al.*, 2006; Stagnari *et al.*, 2014; Zhao *et al.*, 2014a; Lin & Chen, 2015). Its neutral and negative impacts were observed on crop yield especially in humid environments. This will be discussed later.

2.4.2 Effects of mulching on crop yield and WUE

The effects of mulch on crop production have been extensively studied. A review by Iqbal *et al.* (2020) pointed out that mulching can increase agricultural yield by 7 – 47% depending on mulch type, application rate, environment used, and for which crop it is used. However, it is necessary to consider the effects of mulching in specific contexts. In China, plastic mulching has been shown to increase grain yield and WUE of maize by 19% and 16% respectively in dry years but showed no significant difference with the no-mulch in rainy years (Xu *et al.*, 2015). Using straw mulch of 3 cm thickness on a clay loam of a humid subtropic, yield and WUE in cabbage was increased by 22.3% and 29.5% respectively, subsequent upon the 25% increase in soil water storage in the root zone (Biswas *et al.*, 2022). On a sandy loess in the subhumid arid zone of Northwest China, Cai *et al.* (2015) found that applying straw mulch, at an optimum rate of 9 ton/ha, the whole year and only at growing season increased grain yield of spring maize by 4.4% and 2.0%.

Focusing on potato production, a study by Zhao *et al.* (2014b) revealed that full mulching using plastic film in a semi-arid rainfed ecosystem improved potato yield and WUE by 57.4-78.2% and 56.8-70.3% in any ridge-furrow system compared to traditional flat planting without mulch. In China, the world's largest producer of potatoes (FAO, 2022), a meta-analysis was done by Li *et al.* (2018). Their study showed that plastic and straw mulching increased potato yield by 24.3% and 16.0%, and improved WUE by 28.7% and 5.6% respectively. On a regional scale, they found each of these mulch types performed better than the other in some regions compared to others. This variation was attributable to differences in air temperatures, water inputs, soil basic fertility,

and fertilizer application rates during the growing season. Regardless, mulching improves potato production.

Xu *et al.* (2015) found that the significant increase in yield and WUE by plastic mulching is attributable to higher LAI and rapid growth that comes from the improvement of topsoil temperature and moisture. This positive impact is pronounced in dry season whereas in rainy season, it is only noticeable in the early growth stage and over the growing season, yield and WUE is not improved.

Overall, mulching increases crop yield and water use efficiency (Juan *et al.*, 2013 Li *et al.*, 2013; Vijay Kumar *et al.*, 2014). A meta-analysis by Yu *et al.* (2018) revealed that the positive effects of plastic mulch diminish with increasing growing-season precipitation and temperature, while those of straw mulch remains stable, and they therefore recommended that the use of plastic mulch be limited to unfavourable hydrothermal environments. Huang *et al.* (2022) went further to investigate the feasibility of replacing plastic film mulch with straw mulch. From their study, they recommended covering 42% of the field area with straw mulch as optimal replacement for plastic mulch in semi-arid environment. This was after realizing that strip straw mulching increased yield and WUE in wheat by 6.90% and 11.27% compared to no-mulching. Though these values are lower than those obtained with plastic mulch, straw mulch was found to be a sustainable substitute.

It is noteworthy that some studies have shown that mulch may have a neutral or negative impact on soil water balance and crop growth in humid environments due to a reduction in soil temperature, particularly on poorly drained soil or during wet years because of waterlogging (Chen *et al.*, 2007; Giller *et al.*, 2009; Wang & Shangguan, 2015). Therefore, the impact of mulching of soil water balance and crop yield varies. It depends on soil properties, management practices, and climatic conditions of a place. Hence, there is a need to determine optimum application rate for site-specific soils and environmental conditions (Chen *et al.*, 2007).

2.4.3 Interaction between mulching and tillage

Studies have advocated for conservation (reduced or zero) tillage instead of conventional tillage, and choice of tillage practice can influence mulching. Also, organic mulching is preferred because it is environmentally friendly and cheap. It is therefore necessary to consider the interplay between these two practices of sustainable soil management. Zhang *et al.* (2011) found that though crop residue mulching increased soil water storage, it resulted in poor maize development due to

unsuitable thermal conditions in temperate climate areas, under no-till. This is not too surprising as no-till is found to largely reduce crop yield (Pittelkow *et al.*, 2015). In Poland, a temperate region, Glab and Kulig (2008) studied the effect of mulching and tillage on wheat production. Their study revealed that conventional tillage resulted in about 10% increase in yield compared to reduced tillage, but no influence of mulching was observed using conventional tillage. In contrast, the effect of mulching was observed with reduced tillage as grain yield under no-mulch with reduced tillage was 82% of that which was obtained under mulching with reduced tillage. They then recommended mulching with reduced tillage for improved crop yield.

There are numerous studies that have investigated the independent impact of mulching and conservation tillage on soil environment, as well as crop growth, yield and water use efficiency; studies on their interactive effect are very limiting (Du *et al.*, 2022). In addition, the study Pittelkow *et al.* (2015) investigated the limits and principles of conservation agriculture. They reported that there is crop yield gap of 5.7% attributed to no-till and that this yield penalty can be reduced when it is combined with at least one of the other conservation agriculture principles. A gap in their study is that reduced tillage was not considered, and this shows the research gap that needs to be filled - evaluating the combined effect of conservation agriculture principles on different soil and crop properties in different environments.

3.0 MATERIALS AND METHODS

3.1 Experimental site

The experiment was carried out at the experimental site of the Flanders Research Institute for Agriculture, Fisheries and Food (ILVO) in Melle, Belgium (Fig. 1). The study took place on ILVO's bio-parcel (50.987000 N, 3.786791 E) which is an organic agricultural field under conservation agriculture. It is at an elevation of 10.9 m above sea level and has a temperate climate with mild winters and warm summers. From climate data of 1991 – 2020 obtained from the Royal Meteorological Institute in Belgium, it experiences an annual temperature of 11°C, receives about 837.1 mm of annual precipitation and has 189.8 rainy days annually. It has its coldest month to be January (average temperature of 3.7°C) and warmest month to be July (average temperature of 18.7°C). Its driest month is April (average precipitation of 46.7 mm), and wettest month is December (average precipitation of 87.4 mm). The data used in this study was collected between June and September 2023.

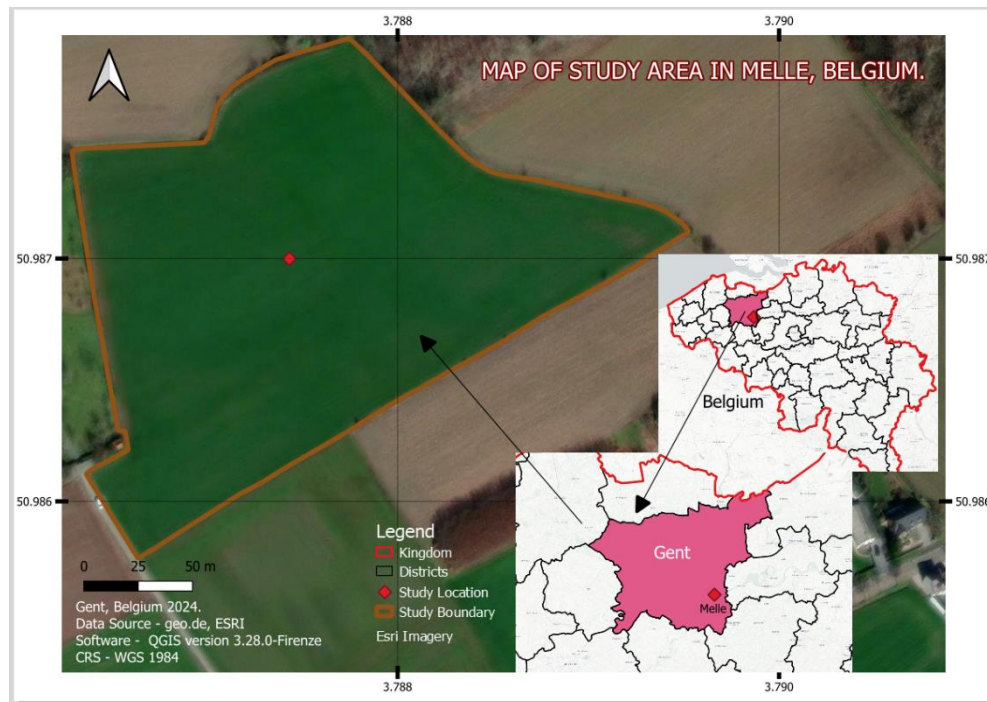


Figure 1: Map showing the experimental field in Melle, East Flanders, Belgium

3.2 Weather condition of the study area during the growing season

The study area received a total rainfall of 314.9 mm and an average daily temperature of 18.6 °C during the 2023 growing season (June 1 to September 29) as shown in Figure 2. The daily rainfall

ranged from 0 to 25.7 mm and daily temperature ranged from 13.1 °C to 25.6 °C. The lowest and highest monthly rainfall was observed to be 24.7 mm and 111mm in June and July respectively. In terms of rainfall amount, June was drier than normal, July was wetter than normal, August was slightly wetter than normal, and September was about normal. June had one of the three lowest precipitation days in June, while July had the highest precipitation days and one of the three highest rainfall amounts in July, both since 1991. June had 16 out of the 32 days of long drought which started in May 2023 (Royal Meteorological Institute of Belgium KMI, 2023).

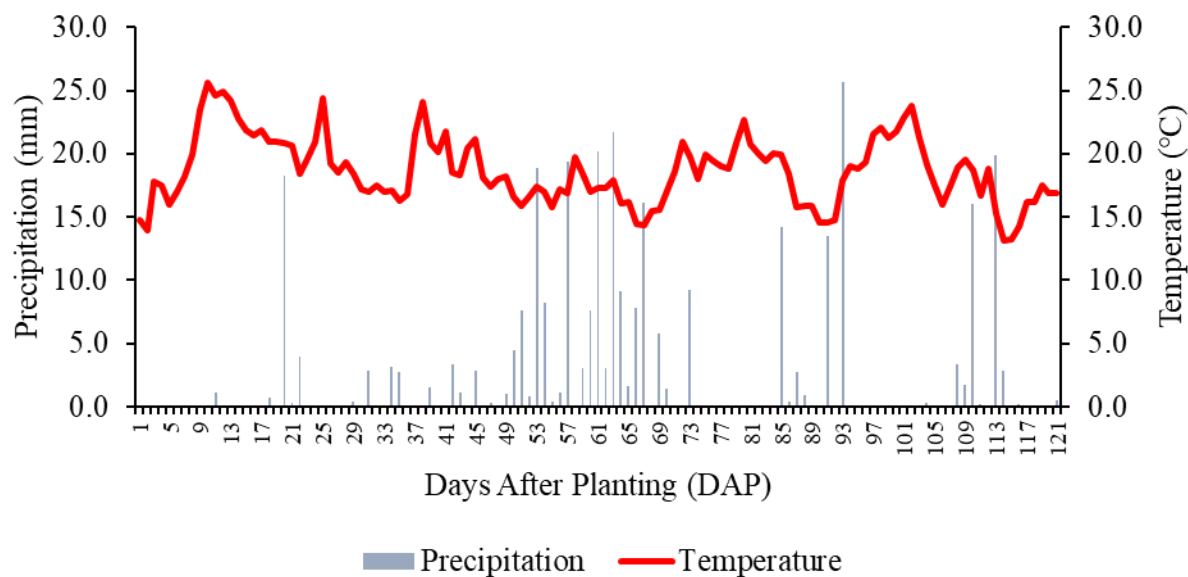


Figure 2: Daily weather condition of the study area during the growing season (June 1 to September 29, 2023)

3.3 Experimental design

The experimental field is a bio-parcel with designations G9 and G10 on the right and left sides respectively. Based on difference in elevation, the field is divided into A and B with the former having a higher elevation. This resulted in four experimental blocks as shown in Figure 3. The experiment was laid out in a randomized complete block design with three treatments of mulch thickness completely randomized to 3 m wide potato strips in each of the four blocks; two blocks (G9A & G9B) were 80 m long and the other two (G10A & G10B) were 50 m long. The treatments include a control (no mulch) and two doses of mulch, 31 tons ha⁻¹ and 65 tons ha⁻¹, resulting in a mulch thickness of 6 cm and 12 cm, respectively. The mulch material was grass-clover (*Trifolium repens*) harvested from a nearby field, chopped and air-dried. At application, the mulch contained

$3.4 \pm 0.3\%$ moisture, $3.3 \pm 0.3\%$ lignin, $29.2 \pm 0.6\%$ cellulose, $26.1 \pm 0.4\%$ hemicellulose, and had a biodegradation potential of $16.7 \pm 1.3\%$.



Figure 3: Experimental layout (mulch thickness indicated by 0 cm (no mulch), 6 cm, and 12 cm within each block designated with G9A, G9B, G10A, and G10B)

Pre-planting operations included land clearing, shallow pass with disc harrow at 15 cm depth, rototilling, and ridging. A variety of potato (*Solanum tuberosum* var. connect) was used as a test crop. It is a yellow-skinned, yellow-fleshed potato. It has medium sized tubers with smooth skin. It is medium-late maturing and high yielding. The planting was done on June 1, 2023, and harvest was done on September 29, 2023.

3.4 Soil physico-chemical properties of the experimental field

The soil of the experimental field is a Cambisol according to the World Reference Base for soil resources. The pit observations revealed that the blocks were similar in horizons – having 3 horizons A (0-10 cm), B (10-35 cm) and C (below 35 cm). In the lower part of the field where the B blocks are located, hydromorphic features were observed indicating anaerobic conditions due to poor drainage and seasonal water saturation. Therefore, the B horizon in the lower part of the field is designated Bg (Fig. 4). According to Belgian soil classification, G9A and G10A have soil type Lcp (moderately dry sandy loam soil without profile development). Parts of G9B and G10B have soil type Ldc (moderately wet sandy loam soil with strongly mottled B horizon) (Fig.5).

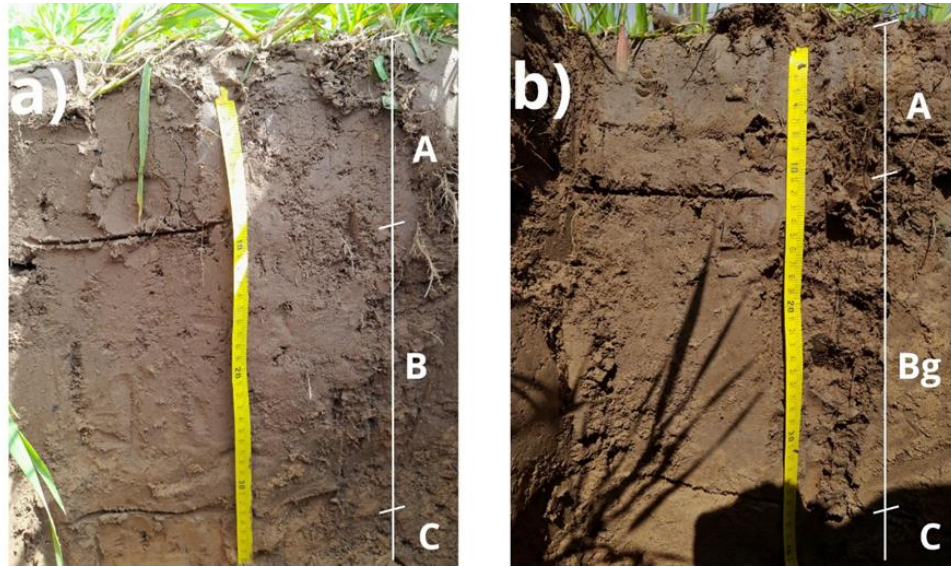


Figure 4: Soil profile of the study area with difference in the B horizon of the upper (a) and lower (b) parts of the field

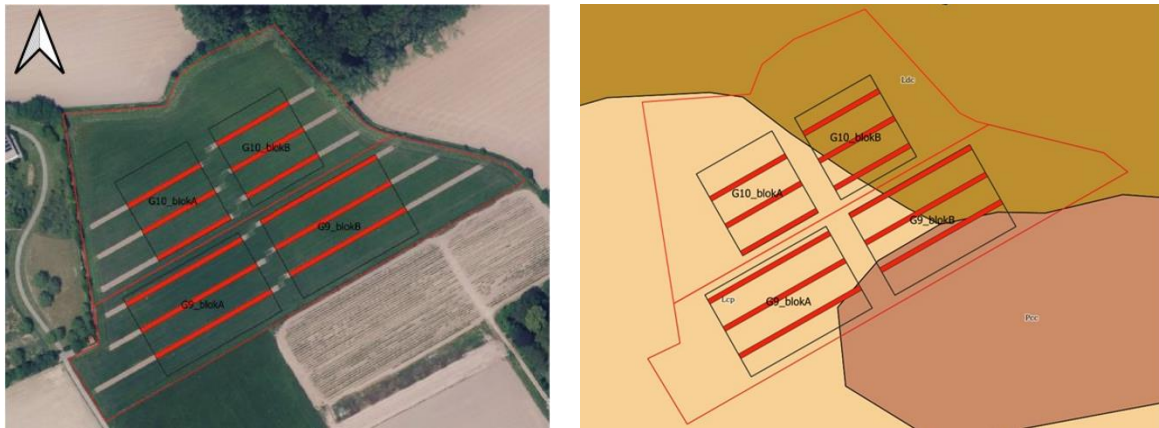


Figure 5: (a) an orthophoto and (b) a soil map of the experimental field

The soil's bulk density and penetration resistance were determined using the core method and penetrometer, respectively, and the blocks were found not significantly different. Generally, the bulk density increased down the profile. It ranged from 1.39 to 1.45 g cm⁻³ in horizon A, 1.59 to 1.68 g cm⁻³ in horizon B, and 1.65 to 1.73 g cm⁻³ in horizon C. At the lowest horizon, G9A was significantly different from that of G10B in bulk density. This difference correlates with the groundwater gradient from the upper part (block A) to the lower part (block B) of the field. The penetration resistance of the field exceeded 2 MPa below a depth of 35 cm. At this resistance,

major limitation is posed to potato root growth (Bengough *et al.*, 2011) as Stalham *et al.* (2007) found potato root growth to be halved at 1.5 MPa and almost halted at 3 MPa. However, the gravimetric moisture content in G9A was lower than in other blocks throughout the profile except at the deepest layer where both G9A and G10A had lower gravimetric moisture content than others. This can be related to the groundwater gradient too. From the core samples, the soil water content at saturation (Sat.), field capacity (FC, taken at matric potential of -10 kPa), permanent wilting point (PWP, at -1500 kPa), and available water content (AWC) were determined (Table 1). Across the profile, the soil holds $0.38 \text{ m}^3 \text{ m}^{-3}$, $0.29 \text{ m}^3 \text{ m}^{-3}$, and $0.09 \text{ m}^3 \text{ m}^{-3}$ of water at Sat., FC, and PWP, respectively. Using the management allowable depletion of 0.65 for potato as recommended by Allen *et al.* (1998) and following the approach by Datta *et al.* (2017) the soil water content at which potato becomes water-stressed, hereafter referred to as MAD, was calculated. Across the profile, it was $0.16 \text{ m}^3 \text{ m}^{-3}$. Table 1 shows the values of these variables per horizon.

Table 1: Some hydraulic properties of the experimental site. (All units are in $\text{m}^3 \text{ m}^{-3}$)

Depth (cm)	Sat.	FC	PWP	AWC	MAD
0 - 10	0.424	0.318	0.081	0.237	0.164
10 - 35	0.351	0.289	0.090	0.199	0.160
35 - 60	0.351	0.273	0.087	0.186	0.152

The soil's saturated hydraulic conductivity (K_s) was determined from the infiltration rate measured using a mini disk infiltrometer (METER Group Inc.) at different tensions of (-6 cm, -4 cm, -2 cm, & -1 cm), as described by Logsdon and Jaynes (1993). The equation used is

$$\frac{q}{\pi R^2} = K_s \exp(\alpha h) + \frac{4K_s \exp(\alpha h)}{\pi R \alpha} \quad (6)$$

where q is the steady-state flow rate [$\text{L}^3 \text{ T}^{-1}$], K_s is the saturated hydraulic conductivity [L T^{-1}], α [L T^{-1}] is a fitting parameter function of the macroscopic capillary length, h is the pressure head or tension [L], and R is the radius of the disk [L].

The saturated hydraulic conductivity (K_s) at Horizon A ranged from 2.8×10^{-4} to $9.2 \times 10^{-3} \text{ cm s}^{-1}$. On average, the blocks follow the order $\text{G10B} (9.1 \times 10^{-4}) < \text{G10A} (2.27 \times 10^{-3}) < \text{G9A} (2.95 \times 10^{-3}) < \text{G9B} (6.07 \times 10^{-3})$ but were not significantly different ($P = 0.0704$) in K_s at 5% significance level. Although at 10% level of significance, a pairwise comparison showed a significant

difference between G9B and G10B (Fig. 6), the blocks were considered not significantly different in Ks.

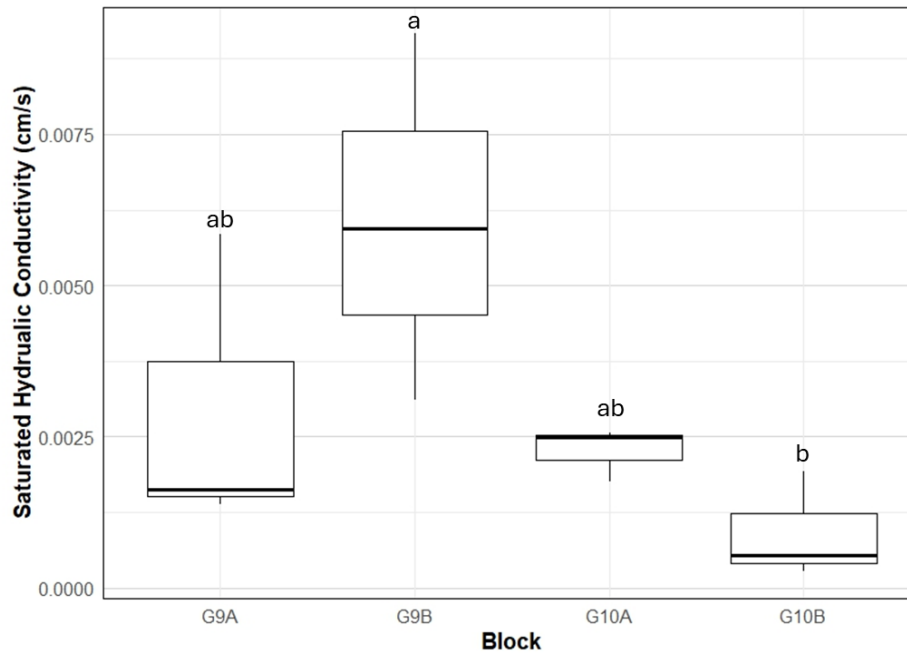


Figure 6: Saturated hydraulic conductivity of horizon A of the experimental field

The soil physical and chemical properties of the study area are shown in Table 2. The soil texture was determined from USDA textural triangle having determined the particle size distribution following the procedure of ISO 11277 which involves sieving and sedimentation. pH of the soil was determined potentiometrically according to ISO 10390; total nitrogen was measured by dry combustion following ISO 13878; organic carbon was determined as a difference between total carbon by dry combustion (ISO 10694) and inorganic carbon (NBN EN 15936); total nutrient concentrations (potassium, magnesium, calcium, phosphorus, etcetera) were measured using 5110 VDV Agilent ICP-OES (Agilent, Santa Clara, CA).

The soil texture is sandy loam through the entire profile of 60 cm. The topsoil (0 –10 cm) had pH-KCl of 5.6 - 6.1, total nitrogen of 0.124% - 0.145%, organic carbon of 1.40% - 1.76%, potassium of 12.9 - 20.9 mg/100 g of dry soil, magnesium of 12.8 - 14.6 mg/ 100 g of dry soil, calcium of 108 – 123 mg/100 g of dry soil, phosphorus of 16.1 - 22.8 mg/100 g of dry soil. The subsoil (10 – 30 cm) has pH-KCl of 5.5, total nitrogen of 0.099% - 0.109%, organic carbon of 1.05% - 1.53%, potassium of 9.2 - 13.6 mg/100 g of dry soil, magnesium of 9.0 - 11.6 mg/100 g of dry soil, calcium of 91 - 115 mg/100 g of dry soil, phosphorus of 17.3 - 27.6 mg/100 g of dry soil.

Table 2: Soil physico-chemical properties of the study area

		Chemical properties						
Block	Depth cm	Total N %	pH- KCl	OC %	K mg/100g	Mg mg/100g	Ca mg/100g	P mg/100g
G9A	0-10	0.124	6.1	1.40	20.9	13.8	116	16.1
G9A	10-30	0.099	5.5	1.10	13.6	9.0	91	17.3
G9B	0-10	0.135	5.6	1.50	12.9	12.8	108	19.9
G9B	10-30	0.103	5.5	1.05	9.9	10.0	113	22.5
G10A	0-10	0.139	5.9	1.76	16.6	13.4	112	20.6
G10A	10-30	0.109	5.5	1.53	9.2	11.0	98	23.2
G10B	0-10	0.145	5.7	1.60	13.0	14.6	123	22.8
G10B	10-30	0.109	5.5	1.11	9.3	11.6	115	27.6
		Physical properties						
Depth cm		Clay <2 μ m %	Silt 2-50 μ m %		Sand 50-2000 μ m %		Textural class	
0-30		7.16	30.82		62.02		Sandy loam	
30-60		7.35	31.88		60.77		Sandy loam	

The soil structural quality (Sq) was determined before and after the treatment using the visual evaluation of soil structure (VESS) method as described by Guimaraes *et al.*, (2011). This involved sampling an undisturbed slice of soil of about 25 cm depth, 20 cm wide and 10 cm thick using a spade, and manually breaking it up (by hand) along fracture planes between aggregates. Layers in each slice of soil were identified and assigned a score using the improved chart by Guimaraes *et al.* (2011) based on an assessment of the ease of breaking-up the soil, the aggregate size and appearance, and visual porosity and roots. An aggregate Sq score for each slice was calculated by multiplying the score of each layer by its thickness and dividing the product by the overall depth. The Sq scores range from 1 (good structure) to 5 (poor suitable). The first visual evaluation of soil structure, before the experiment, indicated that the field was good for agricultural activity and that

the blocks were not significantly different. Of the 9 samples collected across the field, 7 of them had a score of 1.65 - 1.74 with an average score of 1.7. The other two samples had higher scores due to a second layer which was harder to break. A second assessment was conducted six weeks after the application of mulch in each treatment. Unfortunately, due to time constraints, this was conducted without replicates.

3.5 Measurements, data collection and simulation

The weather data were monitored with an Atmos 41 automatic weather station (METER Group, Inc.) installed on the field. The weather variables measured were precipitation (mm), temperature ($^{\circ}\text{C}$), wind speed (m s^{-1}), atmospheric pressure (kPa), vapour pressure (kPa), and solar radiation ($\text{Wh m}^{-2} \text{ day}^{-1}$).

Soil sensors were installed to monitor soil temperature ($^{\circ}\text{C}$) and soil moisture hourly. Per plot, Teros 10 (METER Group, Inc.) and Watermark sensors were installed at three depths (5 cm, 25 cm, and 45 cm) from the soil surface (excluding the ridge height of 10 cm), to monitor the volumetric soil water content and the matric potential, respectively, under each treatment (Fig. 7). In addition, per plot, a Teros 32 (METER Group, Inc.) tensiometer was installed 25 cm deep to determine the matric potential, and a soil temperature sensor was installed at the topsoil to monitor the soil surface temperature. Also, groundwater level was monitored using piezometers with Diver installed at two different positions on the field – G9A and G10B.

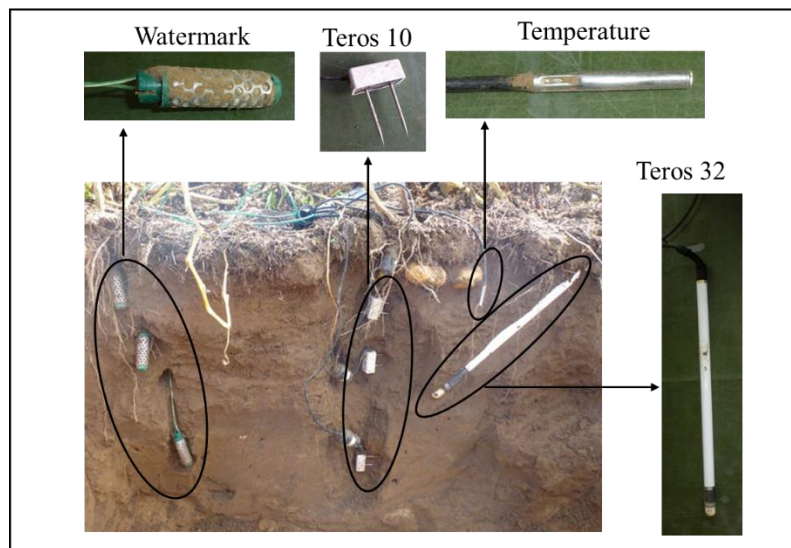


Figure 7: Soil profile showing the positions of the various soil sensors installed per plot

The change in soil water content was considered as the difference in soil water content at the end and beginning of each developmental stage and the entire growing season.

Given that the terrain was flat, it was assumed that there was no runoff. Drainage below and capillary rise into the root zone was assumed to be negligibly small given the very small variation in soil-water content at 55 cm depth (see Chapter 4, Fig. 9c). Evapotranspiration was then determined by adapting the general soil water balance equation:

$$ET = P - \Delta S \quad (7)$$

Notably, the variation in groundwater table depth was minimal, with the latter remaining below 2 m depth at both the upper and lower parts of the field (Fig. 8).

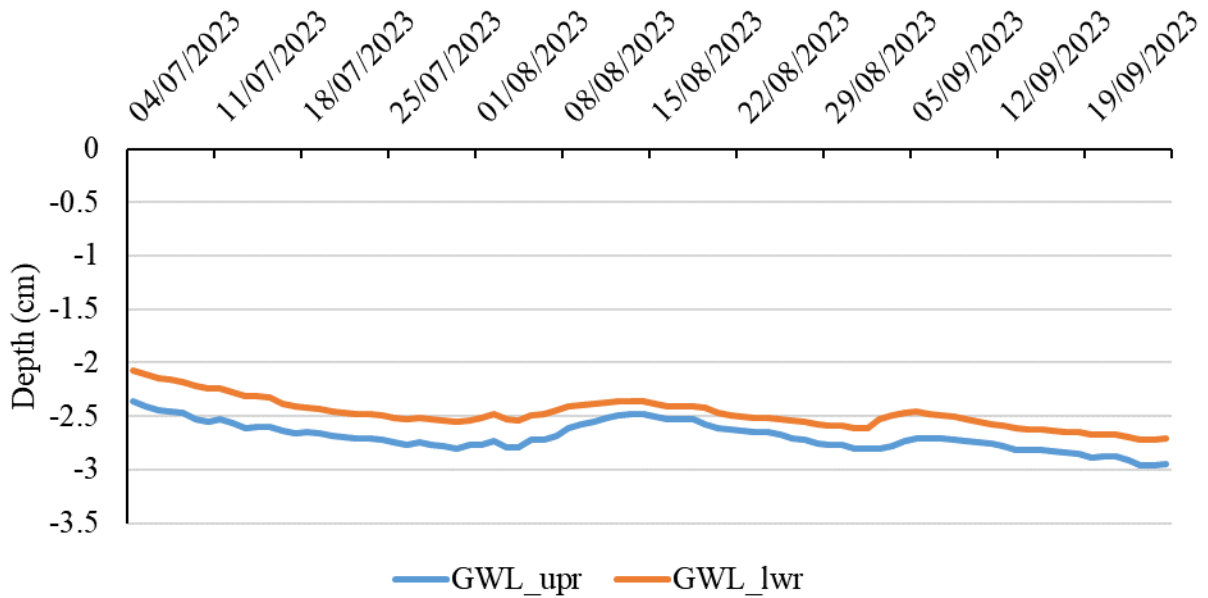


Figure 8: The ground water level of the experimental field through the growing season, taken at the upper (GWL_upr) and lower (GWL_lwr) parts of the field.

Growth and yield parameters of the crop were also collected. These include plant height, leaf area index, and fresh yield of potato. The plant height was measured using a meter rule, the leaf area index was measured using a ceptometer (SS1 SunScan Canopy Analysis System, Delta-T Devices) and the fresh yield of potato was measured using a weighing balance. Water use efficiency (WUE) was determined as a ratio of yield to evapotranspiration:

$$WUE = \frac{Y}{ET} \quad (8)$$

where Y is yield in ton ha⁻¹, and ET is the evapotranspiration (mm) computed using the water balance equation.

To different evaporation from transpiration, canopy cover fraction was determined from measured leaf area index (LAI) following Beer-Lambert's law, with an adapted equation from Garrachón-Gómez *et al.* (2024):

$$CC = 1 - \exp \{ -k \cdot LAI \} \quad (9)$$

where CC is the canopy cover fraction, LAI is the leaf area index and k is the light extinction coefficient taken to be 0.6 following the study by Nyawade *et al.* (2019).

Transpiration and evaporation were calculated using the following equations:

$$E = (1 - CC) \times ET \quad (10)$$

$$E_{adj} = (1 - CC) \times ET \times (1 - Er) \quad (11)$$

$$T = ET - E_{adj} \quad (12)$$

where E is evaporation (mm), E_{adj} is adjusted evaporation (mm), ET is evapotranspiration (mm), T is transpiration (mm), and Er is evaporation reduction factor of 0.35 and 0.5 for 6 cm mulch and 12 cm mulch respectively, as adapted from McMillen (2013).

3.6 Data and statistical analysis

Data processing and statistical analysis were carried out in Excel and R (R Core Team, 2024). Analysis of variance was used as a statistical tool to analyze the data and comparison of means was done using Tukey's Honestly Significant Difference at 5% probability. Data manipulation and visualization were done using the tidyverse set of packages (v1.3.0; Wickham et al., 2019).

4.0 RESULTS

4.1 Effect of mulching on soil structure

The visual evaluation of soil structure showed improvement of the soil structure by mulching (Table 3). The VESS Sq score after the experiment improved as mulch thickness increases in the order 12 cm mulch (1.3) > 6 cm mulch (1.6) > no mulch (2.8), while before the experiment, Sq was 1.7, 2.0 and 1.9, respectively, assessed on the same locations. Due to lack of repetitions in the second evaluation, no statistics can be applied.

Table 3: Effect of mulching thickness on soil structure

	Before treatment (N = 9)	After treatment (N = 3)
No mulch	1.9	2.8
6 cm mulch	2.0	1.6
12 cm mulch	1.7	1.3

N is the number of samples collected.

4.2 Effect of mulching on soil water balance

Figure 9 shows soil water content under different mulch treatment across the field, at each horizon and in the entire profile. Apart from G9A, 12 cm mulch kept the soil water content above the drought stress level (taken at 65% of total plant-available water) in each of the horizon and across the entire profile. Though not as consistent as 12 cm, 6 cm mulch kept the soil water content above stress level in some instances. Without mulch, the soil water content in the 0 – 10 cm and 10 – 35 cm depths fell below MAD in all blocks except G9A, neared PWP in G10A in both depths, and fell below PWP in G10B in the 10 – 35 cm depth. The major falls in the soil water content occurred during periods of no/low rainfall at 25 – 35 DAP, 75 – 85 DAP, and 93 – 108 DAP as shown in Figure 2.

Figure 10 shows the hourly soil water content at 0 – 10 cm, 10 – 35 cm and 35 – 60 cm when there was no rain (September 3 – 8, 93 – 98 DAP). A diurnal pattern was observed in the top 10 cm with constant water content during the night and declining water content during the day due to root activity. In the 10 – 35 cm depth, the diurnal pattern was less pronounced indicating less root activity at that depth. On the other hand, no diurnal pattern observed in the 35 – 60 cm depth, indicating no root activity.

Table 4 shows the means of the water balance components considered over the growing season. Evapotranspiration (ET) was determined using the adapted soil water balance equation (Equation 7). It was determined as the difference between precipitation (P) and change in soil water storage (S). The total amount of rainfall observed during the growing period was 314.2 mm while the change in soil water storage ranged from 1.8 to 5.3 mm and evapotranspiration ranged from 308.9 to 312.5 mm. The treatments were not significantly different in terms of change in soil water storage and evapotranspiration. Notably, as mulch dose increased, S decreased while ET increased. S and ET increased in opposite directions as a response to mulching. In effect, an indirect relationship was observed between S and ET in response to the mulch treatment.

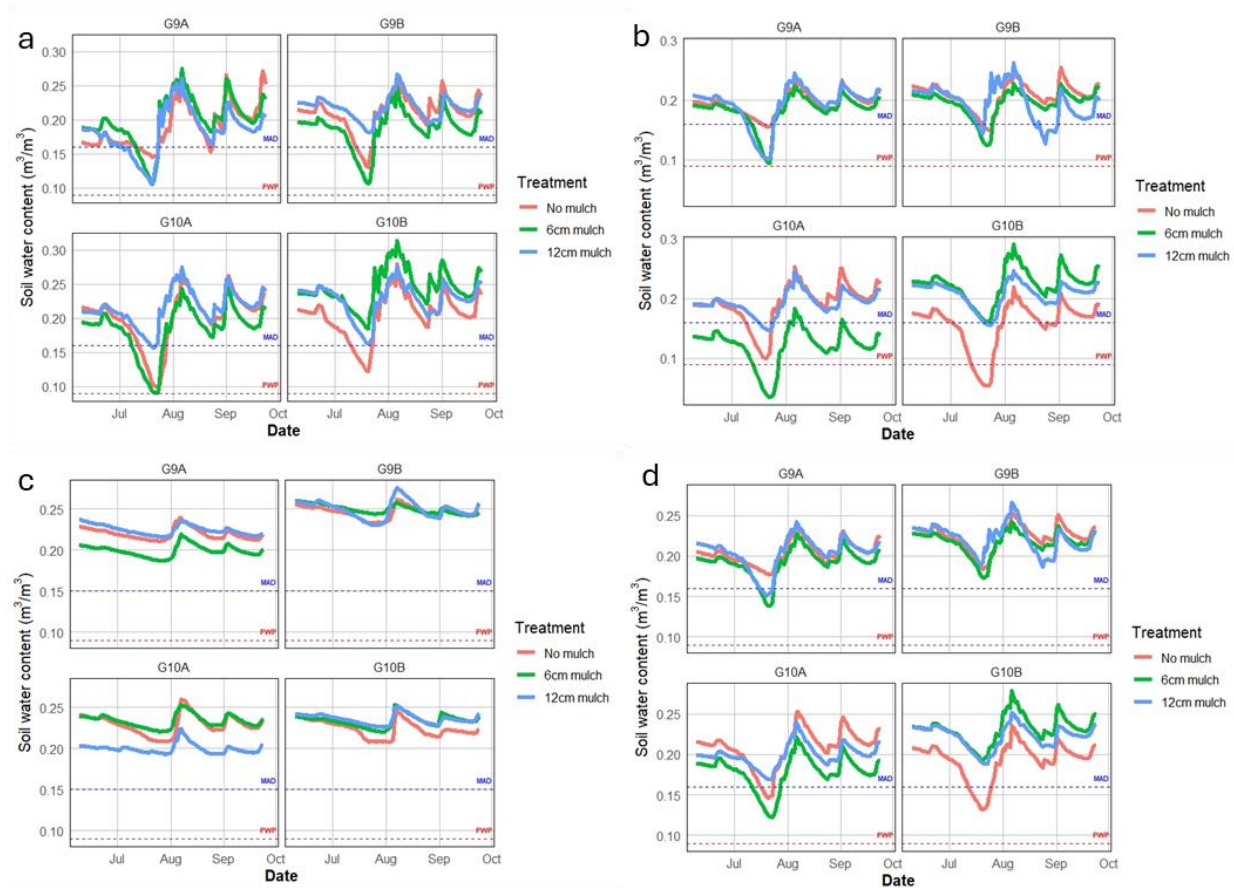


Figure 9: Soil water content under different mulch treatment in (a) Horizon A, 0 - 10 cm; (b) Horizon B, 10 - 35 cm; (c) Horizon C, 35 - 60 cm; (d) entire profile, 0 – 60 cm. Blue and red dashed horizontal lines represent levels at which potato experiences water stress (MAD) and wilting (PWP), respectively.

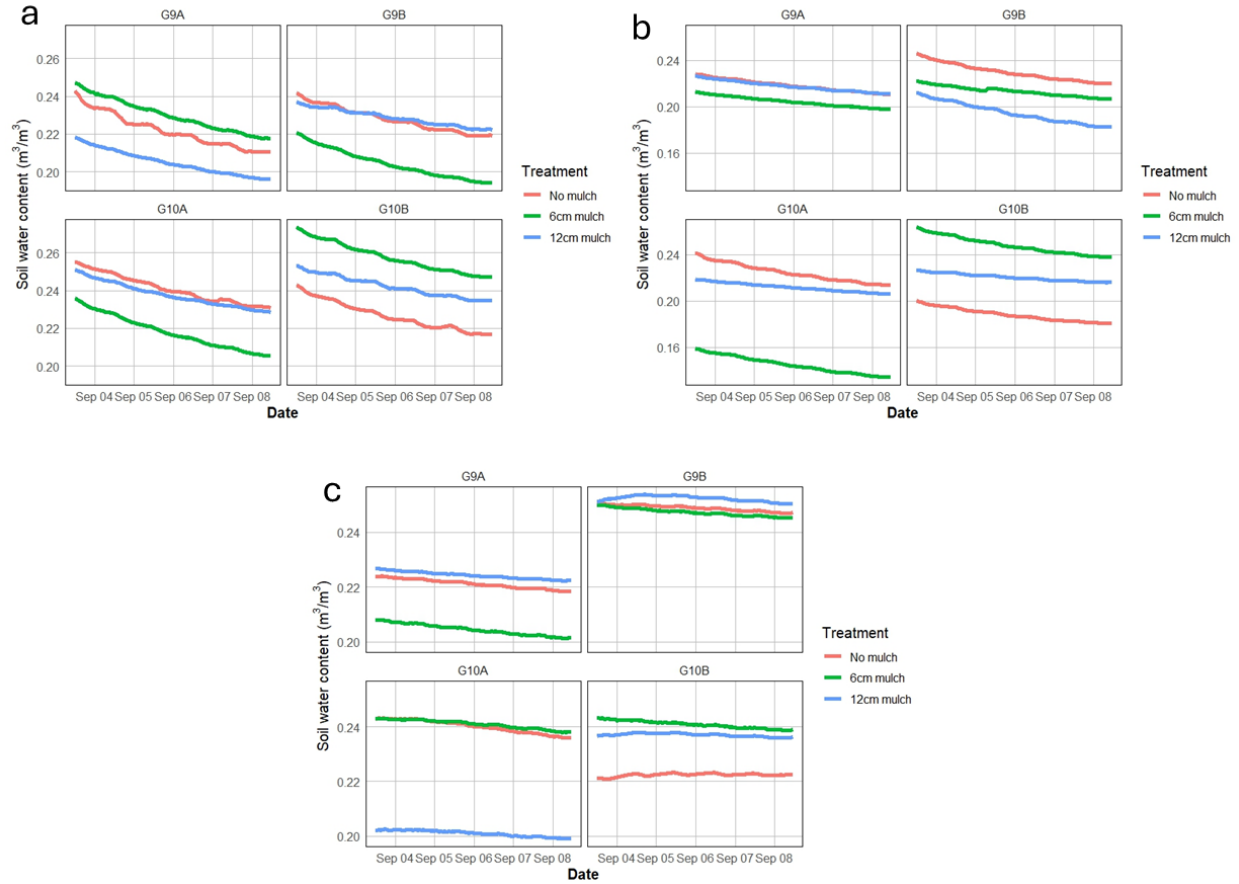


Figure 10: Hourly soil water content during no rainfall in (a) 0-10 cm (b) 10-35 cm (c) 35-60 cm

Table 4: Effect of mulching on soil water balance

Treatment	P (mm)	ΔS (mm)	ET (mm)
No mulch	314.2	5.3	308.9
6 cm mulch	314.2	4.3	310.0
12 cm mulch	314.2	1.8	312.5
		NS	NS

NS- means are not significantly different at 5% probability. P is precipitation, ΔS is change in soil water storage, ET is evapotranspiration.

Figure 11 shows the effect of mulching on evaporation. Under mulched plots, there is a reduction in evaporation compared to bare soil. This resulted in an increase in transpiration under mulched plots compared to bare soil. The treatments were significantly different in terms of cumulative evaporation at every sampling time; likewise, blocks were significantly different except at 25 DAP. In terms of cumulative transpiration, the treatments were significantly different at every sampling

except at 61 DAP while blocks were significantly different except at 25 DAP. Overall, at 81 DAP, evaporation (mm) followed the order no mulch (35.6) > 6 cm mulch (28.4) > 12 cm mulch (13.6). Transpiration (mm) increased in the opposite order: no mulch (219.4) < 6 cm mulch (233.1) < 12 cm mulch (258.5)

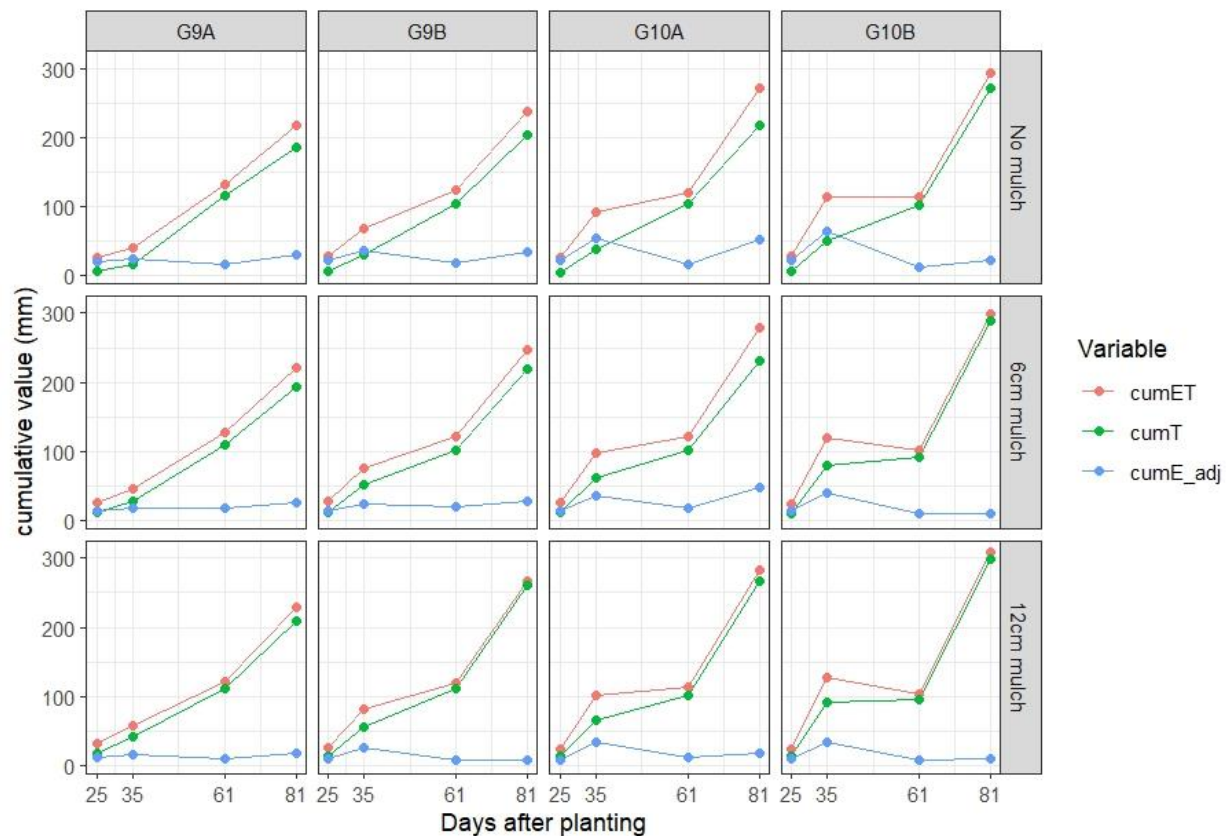


Figure 11: Cumulative values of evapotranspiration, transpiration, and adjusted evaporation (cumET, cumT, cumE_adj) as influenced by mulch treatments

4.3 Effect of mulching on potato growth

The potato reached maturity 120 days after planting. The growth parameters evaluated include plant height and leaf area index. They were measured at 29 and 35 days after planting (DAP), which represent the vegetative growth stage following sprouting, and at 61 and 81 DAP, which represent tuber development stage. At 98 DAP, which is in the maturation stage, only plant height was measured.

4.3.1 Effect of mulching on plant height of potato

A 2-factor ANOVA (treatment and block) showed that the treatments were significantly different at 29 DAP and 81 DAP but the pattern was not consistent. At the latter, the control produced higher

potato plants than mulched plots. Figure 12 shows the effect of mulching on plant height of potato. Usually, there was a trend of 6 cm of mulch improving the plant height whereas 12 cm did not. The blocks were significantly different throughout the growing season. Blocks G9B and G10B produced higher plant height of the potato compared to G9A and G10A. At 29 DAP, block B produced plant height of 27.4 - 35.6 cm while block A produced plant height of 23.8 - 30.4 cm. At 35 DAP, block B produced plant height of 39.9 - 45.1 cm while block A produced plant height of 33.1 - 40.2 cm. At 61 DAP, block B produced plant height of 63.7 - 70.3 cm while block A produced plant height of 58.6 - 66.5 cm. At 81 DAP, block B produced plant height of 64.1 - 68.6 cm while block A produced plant height of 59.3 - 65.4 cm. At 98 DAP, block B produced plant height of 60.8 - 66.4 cm while block A produced plant height of 55.0 - 63.2 cm.

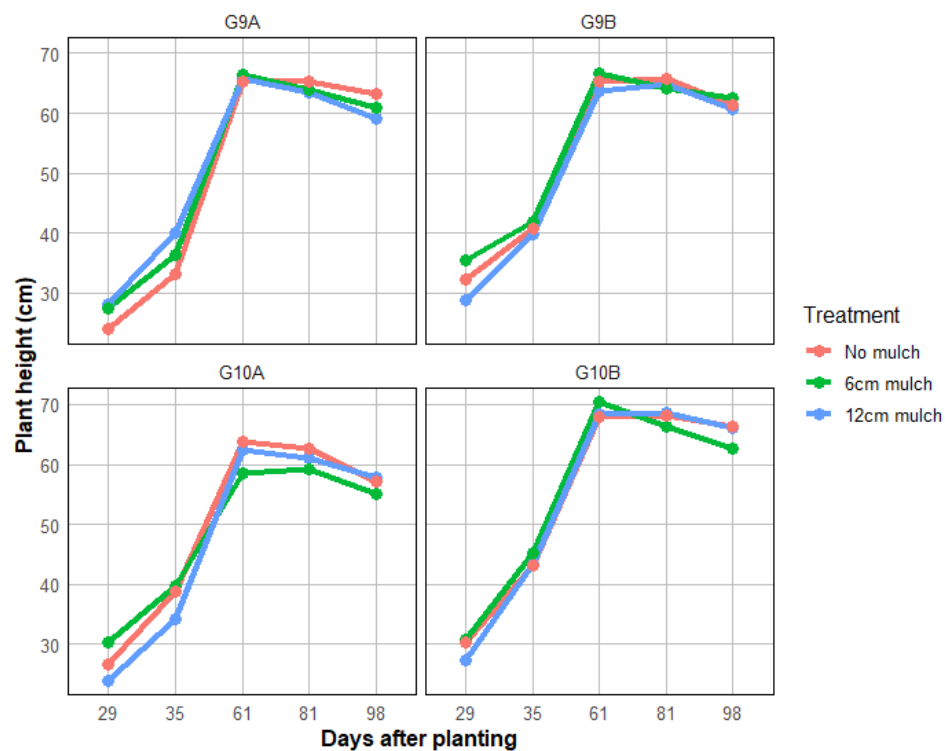


Figure 12: Effect of mulching on plant height of potato through its growing season within each experimental block

Generally, the result shows that potato plant height peaked between 61 and 81 DAP which is a period of tuber development. Afterwards, there was no substantial increase in its height. The B blocks, which is the lower and wetter part of the study area, showed a significant increase in plant height compared to their counterpart A blocks. Across all blocks except G9A, 6 cm mulch resulted

in better plant height especially at the early vegetative stage but further increase in mulch thickness to 12 cm showed no significant difference compared to the control (no mulch).

4.3.2 Effect of mulching on leaf area index (LAI) of potato

Figure 13 shows the effect of mulching on potato leaf area index. Mulching had a significant effect on the leaf area index of potato through its growing season. The treatments were significantly different ($p < 0.05$) at the vegetative stage, 25 and 35 DAP, and highly significantly different ($p < 0.001$) at the tuber development stage, 61 DAP and 81 DAP. Though the block did not impact the LAI at the vegetative stage, the blocks were significantly different ($p < 0.05$) and highly significantly different ($p < 0.001$) at 61 DAP and 81 DAP respectively.

There was a similar trend in G9B and G10B such that both mulch doses show a continuing increase in the LAI of potato as it approaches maturity, but the control reached its peak at the early to mid-stage of tuber development and was beginning to decline or increase at a decreasing rate. In G9A and G10A, all treatments reached their peaks at early to mid-stage of tuber development and did not show appreciable increase in LAI of potato except for 12 cm mulch that showed a continuing increase in G10A.

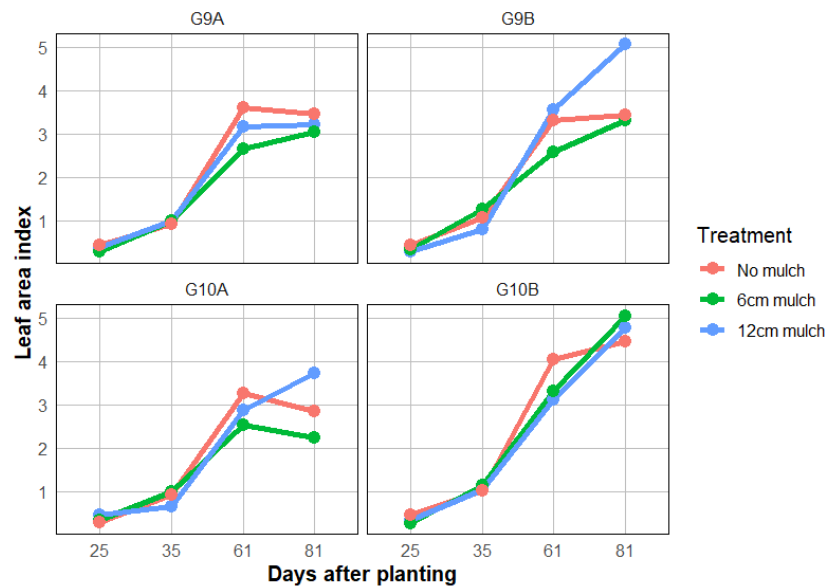


Figure 13: Effect of mulching on leaf are index of potato through its growing season within each experimental block

4.4 Effect of mulching on yield (ton/ha) and water use efficiency (kg/m³) of potato

The potatoes were harvested twice: on August 24, 2023 (about three months after planting) and on September 27, 2023 (about four months after planting). Using the harvest date, block and treatment as factors, a 3-factor ANOVA resulted in significant difference between the harvest date, among the blocks, and among the treatments. The late harvest gave an average yield of 43 ton ha⁻¹ while the early harvest gave an average yield of 34 ton ha⁻¹. Since more yield is expected as the crop approaches maturity and has more time for the tubers to bulk, the statistical analysis was taken a step further.

Using block and treatment as factors, a 2-factor ANOVA on each date showed that from early harvest both treatment and blocks had a significant impact on potato yield, whereas from the late harvest only the block significantly impacted the yield, with the treatments being not significantly different (Fig. 14). In the early harvest the yield from the block followed the order G10B>G9B>G10A>G9A with 42.4, 36.5, 29.7 and 27.5 ton h⁻¹a respectively; the yield increased as the mulch increased with no mulch, 6 cm mulch, 12 cm mulch resulting in 31.4, 33.7 and 37.1 ton ha⁻¹. In the late harvest, the blocks were significantly different in the same order as in the early harvest. G10B, G9B, G10A, G9A resulted in 49.7, 47.7, 39.5 and 35.0 ton ha⁻¹ respectively. Though not significantly different, mulching at a thickness of 6 cm and 12 cm increased the average potato yield from 40.5 to 43.5 and 44.9 ton ha⁻¹ respectively.

The yield of potato in equivalence of kg m⁻² ranged from 3.03 to 5.24 of fresh weight and 0.72 to 1.16 of dry weight indicating an average dry matter content of 22.8%. The result shows a common trend of potato yield increase, in fresh weight, with increasing mulch thickness except in block G10B; but there is no substantial increase in dry weight attributable to the mulch treatment.

Figure 15 shows the water use efficiency (WUE) of this potato variety as a quotient of final yield, in dry weight (kg m⁻²) and the observed evapotranspiration, in equivalent depth of water (m). It ranged from 2.36 to 3.75 kg m⁻³ and there was no pattern observed across the blocks. A two factor ANOVA showed that though the treatments were not significantly different, the blocks were.

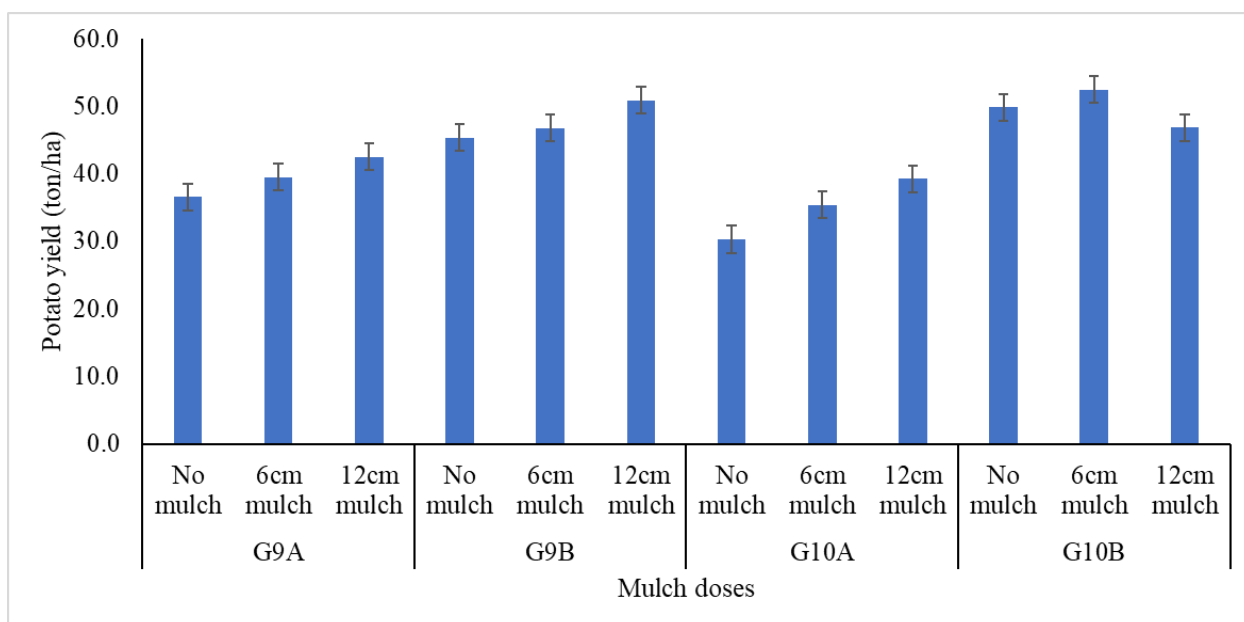
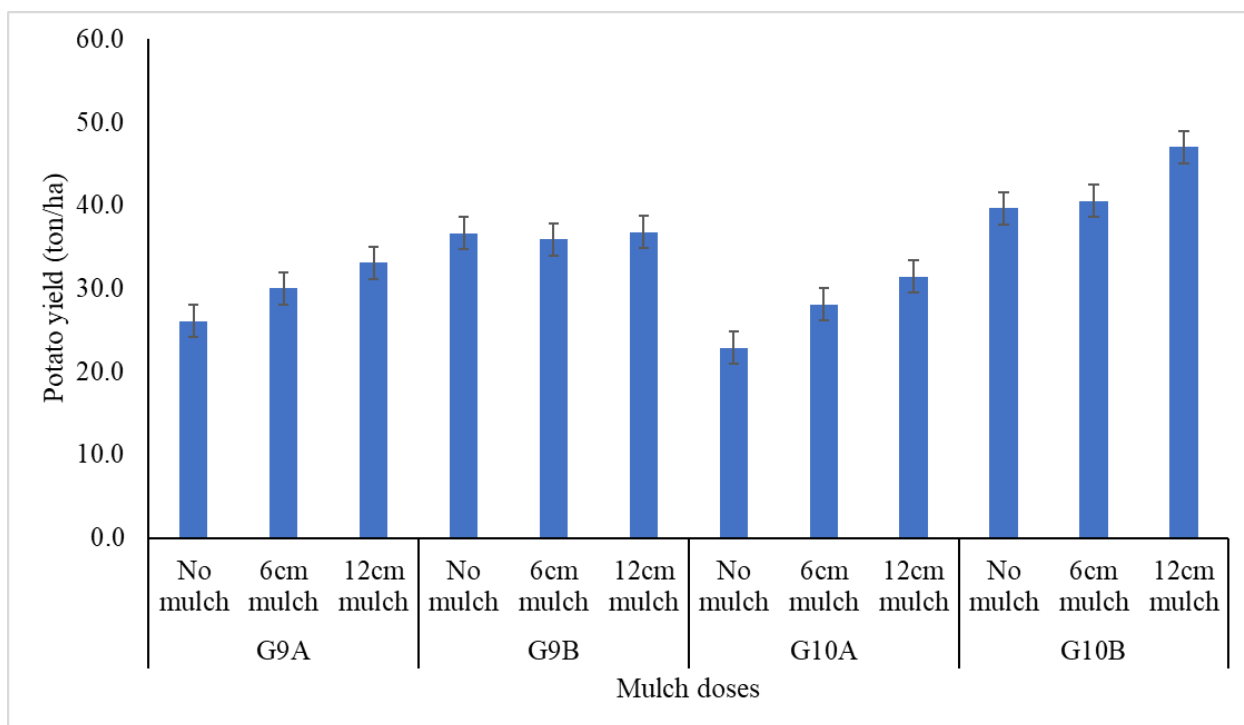


Figure 14: Effect of mulching on potato yield as harvested on (a) August 24, 2023 - 3 months after planting, and (b) September 27, 2023 - full maturity. Error bars indicate standard error

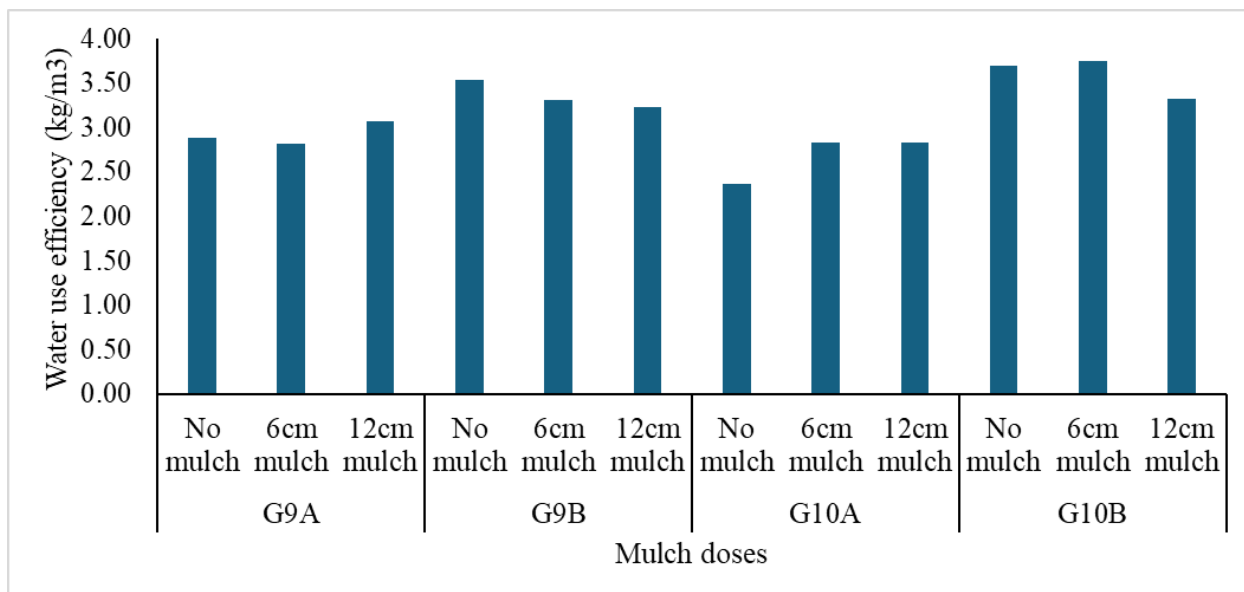


Figure 15: Effect of mulching on water use efficiency of potato.

5.0 DISCUSSION

5.1 Effect of mulching on soil water balance

The results of this study show that mulching plays a role in altering soil water dynamics. The use of clover-grass straw for mulching impacted the rainfall partitioning and soil water balance. Evapotranspiration increased as mulch thickness increased. Mulching tends to conserve more water for plant uptake and transpiration. It does this by impacting soil surface runoff under certain circumstances influenced by land slope, soil type and rainfall intensity. Jordan *et al.* (2010) and Montenegro *et al.* (2013) found straw mulching to reduce surface runoff on a loam and sandy loam respectively, which is like the soil texture of this study. Though runoff was not measured in this study, there was no observable sign of runoff or standing water in puddles. This was probably due to rainfall intensities not exceeding infiltration rates. The maximum daily rainfall during the growing season was 25.7 mm (or on average $2.97 \times 10^{-5} \text{ cm s}^{-1}$), and with a minimum K_s of $2.8 \times 10^{-4} \text{ cm s}^{-1}$ from the blocks, runoff was unlikely. Regardless, mulching can reduce runoff because it increases soil surface roughness and aid infiltration.

Drainage was assumed to be zero given the limited variation in water content below the rootzone. Notwithstanding, Montenegro *et al.* (2013) found drainage to be much lower for bare soil treatment compared to mulched plots, and that higher mulching produced higher drainage volumes. Also, Zhang *et al.* (2007) found straw mulch to increase deep percolation up to 15% on a silt loam. Likewise, capillary rise must have been minimal if any. While there may be several explanations to this, this study rather focused on how mulching impacts evapotranspiration.

Using the adapted soil water balance equation, total ET for the growing season ranged from 308.9 mm to 312.5 mm. From the measured data, an increase in ET was found to be an effect of mulching but it was not significant. This was similar to what was observed when mulching was used in potato production in China (Li *et al.*, 2018), where 3.2% increase in ET by mulching was not significant. More site-specific studies have shown that mulching can increase or decrease ET based on the climate and soil of the study area. For instance, 3 cm thick straw mulching decreased ET by about 6% on a clay loam in humid subtropic region of India (Biswas *et al.*, 2022). And this reduction was attributable to the reduction in evaporation as a component of ET.

This study confirmed a significant reduction in evaporation and proportionate increase in transpiration as an effect of mulching. This means that the increase in ET as an effect of mulching was due to more water uptake by the plant for transpiration. The ability of clover grass mulching to reduce evaporation and increase transpiration can be attributed to how it improved the soil structure. This could have been enhanced because the field has been under reduced tillage which is known to improve soil macropore system, aggregate stability and infiltration capacity (Blanchy *et al.*, 2023). Premised on the tillage system, mulching must have regulated water loss to the atmosphere and moderated heat transfer from the atmosphere. The heterogeneity of the field made the impact of mulching varied from block to block. In G9A and G10A, some disparities were observed at the 0 – 10 cm and 10 – 35 cm depths around the drought period. There seems to be higher resilience to drought under bare soil. While these disparities were unexpected, they are attributable to higher soil disturbance during soil sensors installation. This impacted plant growth around the point of sensor installation, thereby affecting root water uptake and soil water dynamics for that period. Nevertheless, mulching was promising in conserving soil water above a threshold below which potato crop would experience water stress.

5.2 Effect of mulching on potato growth and yield

While there are better indicators of crop development, plant height and leaf area index are useful indicators in evaluating crop growth including potatoes. They are simple, fast to measure, and show how well a plant responds to water and nutrients in the presence of light. The leaf area index is a ratio of a plant's total leaf area to the land area the plant occupies. It indicates how well a plant photosynthesizes, which is directly related to how much photosynthates the plant uses for fruit (tuber) formation. It is useful in yield estimation among others (Herrmann *et al.*, 2011).

The results of this study reveal that the block had a significant effect on potato growth with the lower (wetter) part of the field producing potatoes with higher plant height and LAI. Comparing the wetter part (B blocks) to the drier part (A blocks), potato height increased by about 16% in the sprouting and vegetative stages. Beyond that, the increase in potato height as influenced by the wetter moisture regime was about 7%. This is because at the later stages, the potato directed its resources towards tuber formation and bulking rather than shoot growth. Similarly, the wetter part had a 10% and 41% increase in LAI at the early and late tuber development stages respectively.

There was a significant effect of the treatment on LAI throughout the growing season but on the plant height, it was only significant for the first month when the crop was in the sprout development-early vegetative stage. And this was the month the crop received the lowest amount of rain. The pattern in which mulching impacted LAI was not consistent through the developmental stages. However, it is worthy to note that the wetter moisture regime as found in B blocks produced significantly higher LAI. And in most cases, potatoes under 12 cm mulch produced the maximum LAI, the ones under 6 cm mulch were quite promising while the ones on bare soil started to decline quite earlier than others, especially under the wetter moisture regime.

Several studies have evaluated the effect of different mulch materials on different growth parameters including ones not considered in this study. Some have found mulching to significantly improve these parameters while others did not (Chakraborty *et al.*, 2008; Xu *et al.*, 2015). Though a review by Bhardwaj (2013) highlighted some studies in which plastic mulching consistently increased plant height, in this study in which organic mulch was used, that was not the case. The effect of the treatment observed on plant height in the first month of growing season showed that application of grass-clover mulch 6 cm thick can improve potato plant height during its early growth stage especially when rainfall is low like in the case of the experiment. At this mulch thickness, the scarce water is conserved for potato growth. Beyond this thickness, there was no appreciable increase in plant height.

It is interesting that the treatment's effect on LAI does not show a consistent pattern throughout the growing season. Notwithstanding, at last sampling which was at tuber development stage (81 DAP), 12 cm mulch produced significantly higher LAI than 6 cm mulch and the control which were not significantly different. This corroborates with findings of Zhang *et al.* (2011) in a study on the effects of field management practices on maize growth on a silt loam in the loess plateau of China. Generally, plastic mulch and mixed (plastic + straw) mulch were found to produce significantly higher LAI than straw mulch and a control which were not significantly different. But during late development stages of maize, straw mulch produced significantly higher LAI. Though there may be concerns as to how continuous leaf production and expansion by potato crop could impede tuber bulking and consequently reduce yield, it is also important that potato crop maximizes its leaf production to enhance its rate of photosynthesis which can potentially increase yield. In the case of this study, LAI was not measured till the end of the growing season to observe

when LAI declined for all treatments. From the late measurement which was 40 days prior to final harvest, we can assume that the potato has enough time for tuber bulking, and the higher LAI observed under mulch could increase yield.

Since the interactive effect of the treatment and block was not consistently significant and did not show a regular pattern, it is hard to conclude on whether antecedent moisture content of the soil could contribute to the effect of mulching on potato growth. Nevertheless, application of 6 cm and 12 cm thick clover grass mulch seems promising in improving potato plant height and LAI respectively. This means that application within the rate range can improve potato growth in the study area.

5.3 Effect of mulching on yield and water use efficiency of potato

Two harvests were done. In the first harvest, which was at 85 DAP (about three months after planting), treatments were significantly different, and blocks were significantly different. 12 cm and 6 cm mulch increased potato yield by 18.2% and 7.3% respectively, compared to bare soil; on average, the wetter moisture regime increased potato yield by 37.9% than the drier part. In the final harvest, which was at maturity (about four months after planting), there was a significant difference among the blocks. On average, the wetter moisture regime increased potato yield by 30.7% more than the drier part. Though the treatments were not significantly different in the final harvest, 12 cm and 6 cm mulch increased potato yield by 10.9% and 7.4% respectively. Overall, the yield increased from 34 ton ha⁻¹ in the first harvest to 43 ton ha⁻¹ in the final harvest. This is because the potato had more time to bulk its tuber. Notably, the time of harvest impacted the yield. Potato yield can be maximized by harvesting at maturity, and early harvest can be less productive. While maturation period differs based on variety, harvesting the variety used in this study (*Solanum tuberosum* var connect) at about 120 days after planting helps to maximize yield.

Like yield in the final harvest, the blocks were significantly different in WUE whereas the treatments were not. On average, using dry weight of the yield, the potato had a WUE of 2.8 kg m⁻³ and 3.5 kg m⁻³ in A blocks and B blocks respectively. This is a 25% difference in WUE which suggests that when adequate water is available, productivity of potato can be enhanced.

Although mulching helped to conserve soil water, by reducing evaporation, and improved potato growth, the effect of mulching on the final yield and WUE was not significant. While this was

unexpected, it could be explained by the sufficient rainfall and probable lower soil temperature attributable to the mulching. With enough rainfall, the un-mulched potatoes competed with the mulched ones. Since the latter showed an increase in yield, though not significant, the water conservation effect of mulching would significantly increase yield and WUE under dry conditions. This hypothesis agrees with that of Zhang *et al.* (2011) who found straw mulching to significantly increase maize yield and WUE in the driest season of the three seasons considered. But in the summer of the following year when much more rain fell, straw mulching produced the lowest WUE.

Chen *et al.* (2007) had a similar report when they evaluated the effect of mulching on winter wheat. To prevent water stress and ensure that water was not a limiting factor, they irrigated all treatments at the same time and with similar quantity of water. They found that mulching did not significantly improve yield and subsequently, WUE despite its water conservation effect. Though their treatments were not significantly different, 5 cm and 10 cm straw mulch reduced crop yield. They highlighted that yield reductions can be due to low soil nitrogen levels, cool temperature and rainy weather, and concluded that lower soil temperature was the main factor of yield reduction under mulching.

Studies that have found organic mulching to improve yield and WUE in different crops have highlighted these benefits to be pronounced in semi-arid and arid regions or under tropical and subtropical climates (Chakraborty *et al.*, 2008; Ampofo, 2018). There are also studies that have found mulching to improve potato yield as high as 81.5%, but it was by using plastic mulch under suitable hydrothermal conditions (Kaur & Bons, 2017, El-Beltagi *et al.*, 2022).

From this study, 6 cm thick clover grass mulch increased potato yield by 7.3% and 7.4% in the early and late harvest respectively, while 12 cm thick clover grass increased potato yield by 18.2% and 10.9% in the early and late harvest respectively. Though the difference in the last harvest was not significantly different, applying clover grass mulch is promising in improving potato yield in the study area.

Though this study could not establish a direct relationship between water conservation by mulching and the potato yield, it was evident that the moisture regime played a role in potato yield. The wetter part of the field produced higher LAI in the potato, and there was a strong correlation

between the LAI at 81 DAP and yield ($R^2 = 0.770, 0.818$) at both first and second harvest (Fig. 16).

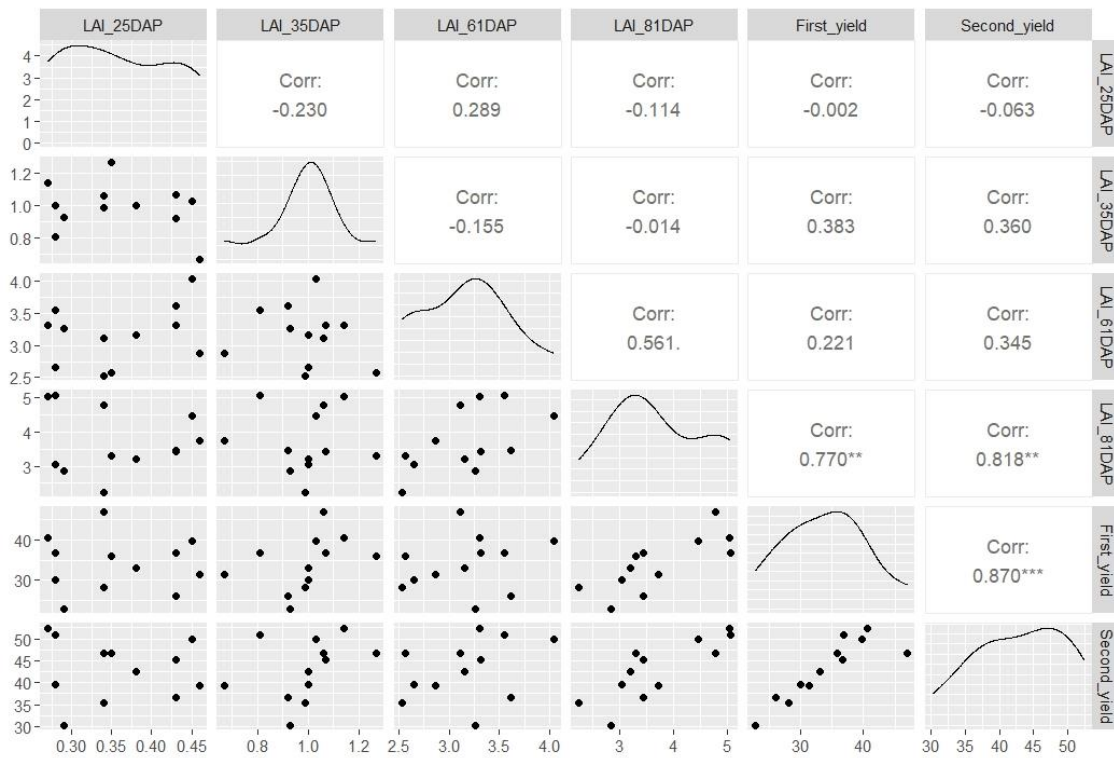


Figure 16: Correlation between leaf area index and yield of potato.

6.0 CONCLUSION

This study revealed that there is an interplay of many factors in the growth, development and yield of potato, like in other crops. One of these is the heterogeneity of soil hydraulic properties. The experimental field showed some heterogeneity in soil hydraulic properties, and this impacted the availability and transport of soil water for plant uptake. It contributed to the differences observed in the impact of mulching on the field.

Overall, mulching improved the soil structural quality (Sq). The Sq of the mulched plots improved under both 6 cm and 12 cm grass-clover mulch while that of the bare soil declined. Despite the field's heterogeneity, mulching improved soil water content and prevented drought stress in the potato at periods of low rainfall. In the drier part of the field, 6 cm mulch could not prevent drought stress during low rainfall at the vegetative to tuber initiation stage. This is because the temperature was relatively high at this period, and the antecedent soil moisture and the little rain could not keep the soil moist above management allowable depletion. On the other hand, 12 cm mulch outperformed other treatments in preventing drought stress.

For a crop such as potato, LAI is a better indicator of growth and development than plant height. This study revealed that 12 cm grass-clover mulch significantly improved LAI in potato compared to 6 cm mulch and the control which were not significantly different. The potato attained a maximum LAI of 4.18 under 12 cm mulch but attained 3.54 and 3.37 under no mulch and 6 cm mulch respectively. Also, this study revealed a strong correlation (> 0.70) between LAI and potato yield. In the final harvest, the potato produced an average yield of 43 ton ha⁻¹ although 6 cm and 12 cm mulch increased the yield by 7.4% and 10.9% compared to 40.5 ton ha⁻¹ from bare soil. In terms of water productivity, the 6 cm mulch outperformed other treatments – having WUE of 3.18 kg m⁻³ compared to others which both had WUE of 3.12 kg m⁻³ each. It is important to note that potatoes in the drier part of the field performed less than others in terms of plant height, LAI, yield and WUE.

Summarily, this study revealed that organic mulching of potato at a thickness of 6 cm to 12 cm is promising in conservation soil water, and improving the growth, yield, and water productivity of potato in the study area. It is recommended that farmers in the Flemish agricultural context employ mulching under reduced tillage system to build agriculture's resilience to climate change. Future studies should consider how soil temperature and nutrient availability would impact the effect of

mulching on soil water balance and crop growth. Given that this study was conducted under a relatively normal year in terms of rainfall, with one month being exceptionally wet (July), two months about normal (August and September), and one month (June) being drier than normal, these results are promising in light of climate change in Belgium, where we expect drier conditions in spring and summer compared to those in this study. This study indicates that mulching has a positive effect on yields. In addition, the effects of mulching will be pronounced under drier conditions, while in wet years (which is likely to occur), the effects of mulching should not necessarily be negative. Long term experiments are needed to prove this.

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ANNEXES

7.1 Statistical analysis of plant height

```
> model <- aov(Obs_value ~ Treatment+Block, data = PlantHeight_29DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	1003	501.3	5.40	0.004895	**
Block	3	1868	622.8	6.71	0.000205	***
Residuals	354	32859	92.8			

```
---
signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(Obs_value ~ Treatment+Block, data = PlantHeight_35DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	213	106.6	1.015	0.363	
Block	3	2967	989.1	9.419	5.32e-06	***
Residuals	350	36755	105.0			

```
---
signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(Obs_value ~ Treatment+Block, data = PlantHeight_61DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	20	9.9	0.305	0.737	
Block	3	2416	805.4	24.884	1.24e-14	***
Residuals	354	11458	32.4			

```
---
signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(Obs_value ~ Treatment+Block, data = PlantHeight_81DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	276	137.8	3.188	0.0425	*
Block	3	2008	669.3	15.488	1.73e-09	***
Residuals	354	15298	43.2			

```
---
signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(Obs_value ~ Treatment+Block, data = PlantHeight_98DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	179	89.6	2.307	0.101	
Block	3	3152	1050.8	27.046	9e-16	***
Residuals	354	13754	38.9			

```
---
signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

7.2 Statistical analysis of leaf area index

```
> model <- aov(obs_value ~ Treatment+Block, data = LAI_25DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	0.299	0.14959	4.397	0.0135	*
Block	3	0.006	0.00186	0.055	0.9831	
Residuals	196	6.668	0.03402			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(obs_value ~ Treatment+Block, data = LAI_35DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	1.87	0.9358	4.268	0.0151	*
Block	3	1.62	0.5402	2.464	0.0631	.
Residuals	234	51.30	0.2192			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(obs_value ~ Treatment+Block, data = LAI_61DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	23.52	11.762	17.210	1.26e-07	***
Block	3	7.92	2.642	3.865	0.0102	*
Residuals	201	137.37	0.683			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(obs_value ~ Treatment+Block, data = LAI_81DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	25.01	12.507	12.16	1.03e-05	***
Block	3	88.64	29.547	28.74	1.71e-15	***
Residuals	200	205.63	1.028			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

7.3 Statistical analysis of yield

```
> model <- aov(fresh.tuber ~ Treatment+Block+Date, data = Yield)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	101.6	50.8	8.818	0.00236	**
Block	3	826.3	275.4	47.807	1.69e-08	***
Date	1	478.8	478.8	83.106	5.90e-08	***
Residuals	17	97.9	5.8			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(fresh.tuber ~ Treatment+Block, data = first_harvest)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	66.4	33.20	7.347	0.024375	*
Block	3	414.3	138.09	30.561	0.000495	***
Residuals	6	27.1	4.52			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
> model <- aov(fresh.tuber ~ Treatment+Block, data = second_harvest)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	39.8	19.89	2.385	0.1729	
Block	3	428.3	142.77	17.120	0.0024	**
Residuals	6	50.0	8.34			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

7.4 Statistical analysis of water use efficiency

```
> model <- aov(WUE ~ Treatment+Block, data = SWB)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Treatment	2	0.0096	0.0048	0.086	0.9185	
Block	3	1.5467	0.5156	9.260	0.0114	*
Residuals	6	0.3341	0.0557			

```
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

7.5 Statistical analysis of evaporation

```
> model<-aov(cumE_adj ~ Block + Treatment, data = E_25DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	0.98	0.33	0.252	0.858
Treatment	2	287.05	143.52	110.393	1.85e-05 ***
Residuals	6	7.80	1.30		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
> model<-aov(cumE_adj ~ Block + Treatment, data = E_35DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	1325.5	441.8	16.74	0.00255 **
Treatment	2	671.6	335.8	12.72	0.00695 **
Residuals	6	158.4	26.4		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
> model<-aov(cumE_adj ~ Block + Treatment, data = E_61DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	55.92	18.64	5.452	0.03777 *
Treatment	2	128.11	64.05	18.735	0.00263 **
Residuals	6	20.51	3.42		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
> model<-aov(cumE_adj ~ Block + Treatment, data = E_81DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	949.1	316.4	5.770	0.0335 *
Treatment	2	1011.9	505.9	9.228	0.0148 *
Residuals	6	329.0	54.8		

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

7.6 Statistical analysis of transpiration

```
> model<-aov(cumT ~ Block + Treatment, data = T_25DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	5.46	1.82	0.897	0.495482
Treatment	2	195.52	97.76	48.157	0.000202 ***
Residuals	6	12.18	2.03		

```
---
```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
> model<-aov(cumT ~ Block + Treatment, data = T_35DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	3166	1055.3	45.49	0.000161 ***
Treatment	2	1932	965.9	41.64	0.000304 ***
Residuals	6	139	23.2		

```
---
```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
> model<-aov(cumT ~ Block + Treatment, data = T_61DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	418.1	139.36	13.533	0.00444 **
Treatment	2	47.8	23.92	2.323	0.17900
Residuals	6	61.8	10.30		

```
---
```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

```
> model<-aov(cumT ~ Block + Treatment, data = T_81DAP)
> summary(model)
```

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Block	3	12351	4117	51.25	0.000114 ***
Treatment	2	3146	1573	19.59	0.002344 **
Residuals	6	482	80		

```
---
```

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1